Materials Experience

Fundamentals of Materials and Design

Edited by

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Biography

Elvin Karana is an Assistant Professor in the Faculty of Industrial Design Engineering (IDE) at Delft University of Technology (DUT), The Netherlands. She obtained her Bachelor and Master degrees from the Department of Industrial Design, Middle East Technical University (METU), in Ankara. She undertook her PhD research at DUT, where she developed a 'Meaning Driven Materials Selection Tool' to support designers in their materials selection activities. Some of her major publications can be found in *Materials and Design* journal, *International Journal of Design* and *Journal of Cleaner Production*. Elvin is one of the founders of the Natural Fibre Composites Design Platform in The Netherlands. She is also the developer and Coordinator of the materials library 'Made Of..' within IDE at DUT, Her current research interests include 'effective materials education in design', 'dynamic materials experiences' and 'designing with bio-based materials'.

Owain Pedgley is Associate Professor of Industrial Design at Middle East Technical University (METU), Ankara, Turkey. He undertakes research in the areas of materials and manufacturing for industrial design and user-product experiences, with a special emphasis on musician-instrument interaction. Owain is a partner in the musical instrument innovation project Cool Acoustics. He contributes to design education at bachelor, master and doctoral levels and is experienced in establishing and managing industrially collaborated projects with firms including Bosch und Siemens Hausgeräte, Vestel and Kale. Prior to his academic career, Owain served three years as a product designer in the sports equipment sector.

Valentina Rognoli is an Assistant Professor in the Department of Chemistry, Materials and Chemical Engineering "Giulio Natta" at Politecnico di Milano, Italy, where she conducts research in the field of materials and education. She teaches in the School of Design within Politecnico di Milano. After two years at Enzo Mari's studio in Milan, in 2000 Valentina started her academic activities focused on materials and their expressive-sensory dimension. In her PhD research she

developed an ‘Expressive-Sensorial Atlas of Material’ as a tool to improve materials education in the field of design. Valentina also developed and coordinated ‘Materiali e Design’, the materials library of Politecnico di Milano. Her current research topics delve into materials and their relationship with innovation, emotions, and sustainability.

Foreword: Materials Experience—Fundamentals of Materials and Design

We live, in the West, in a world with a surfeit of products. You want an electric kettle? You have a choice of at least 30, all with more or less the same technical specification. A vacuum cleaner? There are at least 30 models of those too. A refrigerator? A car? The same story.

Given this surfeit, how do consumers choose the products they buy? The answer has to do with value. A product has a cost—the outlay in manufacturing and marketing it. It has a price—the sum at which it is offered to the consumer. And it has a value—a measure of what the consumer thinks it is worth. Consumers buy products that they perceive as having a value (to them) that most exceeds their price. But what determines value? Sound technical design clearly plays a role: the product must work properly and be safe and economical. Beyond that, the product must be easy to understand and operate, and these are questions of usability. And there is a third requirement: that the product gives satisfaction, that it enhances the life of its owner. The value of a product is a measure of the degree to which it meets or exceeds the expectation of the consumer in all three of these—functionality, usability, and satisfaction. One might think of the three as forming the character of the product. It is very like human character. An admirable character is one who functions well, interacts effectively, and is rewarding to be with. An unappealing character is one that does none of these. Unappealing products are kept only as long as they are useful and are then cast aside. By contrast, as Valentina Rognoli and Elvin Karana point out in Chapter 11 of this remarkable collection of essays, well-designed products are cherished; they can acquire value with age, and—far from becoming unwanted—can outlive their design-life many times over. The auction houses and antique dealers of New York, London, and Paris thrive on the sale of products that, often, were designed for practical purposes but are now valued more highly for their aesthetics, associations, and perceived qualities. People do not throw away things for which they feel emotional attachment.

The rapid turnover of products we see today is a comparatively recent phenomenon. In earlier times, furniture was bought with the idea that it would fill the needs not just of one generation but of several—treatment that, today, is reserved for works of art. A wristwatch, or a gold pen, was a thing you used for a lifetime and then passed on to your children. No more. Changing lifestyles and fashions, promoted by seductive advertising, reinforce the desire for the new and urge the replacement of the old. Industrial design carries a heavy responsibility here—it has, at certain periods, been directed toward creative obsolescence, designing products that are desirable only if new, and urging the consumer to buy the latest models, using marketing techniques that imply that acquiring them is a social and psychological necessity. As Jonathan Chapman points out in Chapter 10, this has led to an ecological crisis, a society that consumes natural resources at an accelerating rate, not conserving them but degrading and discarding them, with environmental consequences that are now a cause of real concern.

Here, the concept of the material life cycle and life cycle assessment, explored by Carlo Vezzoli in Chapter 8, is helpful. The idea of a life cycle has its roots in the biological sciences. Living organisms are born; they develop, mature, grow old, and, ultimately, die. The progression is built in—all organisms follow broadly the same path—but their development and their behavior, life span, and influence, depend on their interaction with their environment—the surroundings in which they live. Life sciences track the development of organisms and the ways in which they interact with their environment. Materials in products have a rather similar life story. Ore, feedstock, and energy are drawn from the natural resources of the planet and processed to give materials. These are subsequently manufactured into products that are distributed, sold, and used. Products have a useful life at the end of which they are discarded, a fraction of the materials they contain perhaps entering a recycling loop, the rest committed to incineration or landfill.

Increasing global population and affluence have inflated consumption to a level that is not, in the long term, sustainable. The average ecological footprint[1] per person in developed nations now exceeds the per capita carrying capacity of the planet, although the consequences of this are not yet evident, masked by the many nations with far lower footprints. Part of the footprint is technology driven, a direct result of increased transport, manufacture, and domestic consumption. This perception has, over the last 20 years, motivated many projects aimed at more sustainable technology: lightweight design to provide sustainable transport (Erik Tempelman, Chapter 18), "intelligent" materials with sensing and energy-harvesting ability (Sybrand van der Zwaag, Dan van den Ende, and Wilhelm Albert Groen, Chapter 16), biobased materials to replace those that draw on nonrenewable resources (Prabhu Kandachar and Sascha Peters, Chapters 7 and 13), and an increasing emphasis on material-efficient design. There is also a growing movement, in parallel with these technical responses to environmental concerns, to explore the creative use of what you might call "waste"—material that is discarded by the first owner of a product but which, in the hands of an imaginative designer, can be reused or reprocessed to make new, more environmentally friendly objects (David Bramston and Neil Maycroft in Chapter 9, and Jakki Dehn in Chapter 12).

One might pause at this point to reflect on the origins of waste. A product reaches the end of its life when it is no longer valued. The cause of death is, frequently, not the obvious one that the product just stopped working. The life expectancy is the least of[2]

- The physical life, meaning the time in which the product breaks down beyond economic repair;
- The functional life, meaning the time when the need for it ceases to exist;

[1] The ecological footprint is an indicator of human pressure on the environment. It is a measure of the biologically productive land and marine area required to produce the resources and absorb the waste of a human population.

[2] This list is a slightly extended version of one presented by Woodward D.G. (1997), "Life cycle costing", *International Journal of Project Management*, Vol. 15, pp.335–344.

- The technical life, meaning the time at which advances in technology have made the product unacceptably obsolete;
- The economic life, meaning the time at which advances in design and technology offer the same functionality at significantly lower operating cost;
- The legal life, the time at which new standards, directives, legislation, or restrictions make the use of the product illegal;
- And finally the desirability life, the time at which changes in taste, fashion, or aesthetic preference render the product unattractive.

One obvious way to reduce resource consumption is to extend product life by making it more durable and more adaptable to change in the surrounding world. But durability means survival in more than one sense: we have just listed six. Materials play a role in them all, particularly the last.

As Aart van Bezooyen (Chapter 19) suggests, materials inspire design. Painters paint with pigment; writers paint with words; designers paint with materials. A diverse palette, a mastery of words, and a comprehensive grasp of materials are, for each, tools of the trade—necessary professional skills. But the most exciting creations are not usually those that use a radiant rainbow of colors, or a lavish lexicon of words, or a cluttered cornucopia of materials. Simplicity and restraint can be more appealing than drama and display. Thus good design can be inspired by a single material, as in the "Frida" chair that Elvin Karana, Owain Pedgley, and Valentina Rognoli choose, in the Introduction to this volume, as one of the exemplars of products that had particular appeal to them.

We interact with materials through products. The interaction involves both the technical and aesthetic attributes of the product. Aesthetics (like "inspiration") is a difficult word, having too many shades of meaning to convey a sharp message, yet there seems to be no other that quite captures the sensory attributes of materials and products. What do we mean by it? It is easier to start with its opposite: anesthetics. Anesthetics numb the senses, suppress feeling; anesthesia is a lack of all sensation. Aesthetics do the opposite; they arouse interest and stimulate and appeal to the five senses, particularly the sense of vision. It is through the senses that we experience materials. Designers manipulate these senses—and the reactions to each sense—to create a product's personality. Paul Hekkert and Elvin Karana (Chapter 1), Henrik Schifferstein and Lisa Wastiels (Chapter 2), and Blaine Brownell (Chapter 5) explore in depth the relationships between materials and experience and the ways they can be manipulated. Aesthetic experience might seem a difficult attribute to measure but that is only partly true. The sense of the soft or hard, cool or warm, dull or bright, matt or shiny can be quantified and linked to material properties. Zoe Laughlin and Philip Howes (Chapter 4) describe what can be learned from a study of these sensoaesthetic attributes of materials and how closely they can be linked to the physical, chemical, and thermal properties familiar to the materials scientist and engineer. This exploration of subjective feeling and underlying physical properties is also raised in the studies of Hengfeng Zuo, Tony Hope, and Mark Jones, described in Chapter 3, concerning the interaction of geometry and material properties with emotional response.

These interactions evoke the aesthetic response to a product but that is not all. A product has perceived attributes and associations—it might be seen as "feminine", or "classical", or "avant-garde", or "decadent". It is these, in part, that give it its personality, something designers work hard to create. But can a material be said to have perceived attributes or indisputable associations? A personality? At first sight, no—it only acquires them when used in a product. Like an actor, it can assume many different personalities, depending on the role it is asked to play.

And yet… think of wood. It is a natural material with a grain, a surface texture, color, and feel that other materials do not have. It is tactile—it is perceived as warmer than many other materials, and seemingly softer. It is associated with characteristic sounds and smells. It has a tradition; it carries associations of craftsmanship. And it ages well, acquiring additional character with time. Objects crafted from wood are valued more highly when they are old than when they are new. There is more to this than just aesthetics; there are the makings of a personality, to be brought out by the designer, certainly, but there none the less.

And metals… metals seem cold, clean, precise. They ring when struck. They reflect—particularly when polished. They are accepted and trusted; machined metal looks strong, its very nature suggests it has been engineered. The strength of metals allows slender structures—the cathedral-like space of railway stations or the span of bridges. Metals can be worked into flowing forms like intricate lace or cast into solid shapes with integral detail and complexity. And—like wood—metals can age well, acquiring a patina that makes them more attractive than when newly polished—think of the bronze of sculptures, the pewter of mugs, the lead and copper of roofs.

And ceramics or glass? They have a long tradition: think of Greek pottery and Roman glass. They accept almost any color; this and their total resistance to scratching, abrasion, discoloration, and corrosion gives them a certain immortality, threatened only by their brittleness. They are—or were—the materials of great craft-based industries: Venetian glass, Meissen porcelain, and Wedgwood pottery, valued, sometimes, as highly as silver. And ceramic today has an additional association—that of advanced technology: kitchen stove tops, high-pressure/high-temperature valves, space shuttle tiles… materials for extreme conditions.

And, finally, polymers. "A cheap, plastic imitation" used to be a common phrase—and that is a hard reputation to live down. It derives from an early use of plastics, to simulate the color and gloss of Japanese handmade pottery, much valued in Europe. Commodity polymers are cheap. They are easily colored and molded (that is why they are called "plastic"), making imitation easy. Unlike ceramics, their gloss is easily scratched, and their colors fade—they do not age gracefully. You can see where the reputation came from. But is it justified? No other class of material can take on as many characters as polymers: colored, they look like ceramics; printed, they can look like wood or textile; metalized, they look exactly like metal. They can be as transparent as glass or as opaque as lead, as flexible as rubber or as stiff—when reinforced—as aluminum. But despite this chameleon-like behavior they do have a certain personality: they feel warm—much warmer than metal or glass; they are adaptable—that is part of their special character; and they lend themselves, particularly, to brightly colored, lighthearted, even humorous, design.

So there is a character hidden in a material even before it has been made into a recognizable form—a sort of embedded personality, a shy one, not always visible, easily concealed or disguised, but one that, when appropriately manipulated, can contribute to good design. Rob Thompson and Elaine Ng Yan Ling (Chapter 14) develop this theme, exploring, as they put it, some of the most exciting collisions between design, engineering, and materials science. Daniel Schodek and Julian Vincent (Chapters 15 and 17) carry it further with visions of the design opportunities suggested by nature and made possible by nanotechnology. Even more exciting are the developments described by Sybrand van der Zwaag and his coauthors (Chapter 16) of the potential for bringing materials to life, able to sense and actuate like human nerves and muscle, by embedding piezoelectric particles in polymer fibers and fabrics.

How, then, do designers choose their materials? Studies of the ways in which the human brain manipulates information suggest two rather different processes. The first, the domain of the left hemisphere of the brain, utilizes verbal reasoning and mathematical procedures. It moves from the known to the unknown by analysis—an essentially linear, sequential path. The second, the domain of the right hemisphere, utilizes images, both remembered and imagined. It creates the unknown from the known by synthesis—by dissecting, recombining, permuting, and morphing to form new images with new associations. The first way of thinking, the verbal-mathematical, is based on learned rules of grammar and logic. The second way of thinking, the visual, makes greater use of the imagination; it is less structured but allows greater conceptual jumps through free association.

The literature on materials selection suggests a similar pattern. The technical designers' instinct is for methods that are systematic and deterministic. They are trained in mathematical modeling and numerical analysis—they are tools of their trade. As Eddie Norman (Chapter 21) and Luigi De Nardo and Marinella Levi (Chapter 22) discuss, selection via deductive reasoning is now a well-developed route to meeting technical design requirements and powerful software and databases exist to support it. It has great strengths. It is systematic. It is based on a deep ("fundamental") understanding of the underlying phenomena. And it is robust—provided the inputs are precisely defined and the rules on which the modeling is based are sound. This last provision, however, is a serious one. It limits the approach to a subset of well-specified problems and well-established rules. And—as Jonathon Allen points out in Chapter 6—there is more to creative selection than this; there are the deeper aesthetic, cultural, emotional, and social dimensions. There the analytical method breaks down and methods of a different sort are needed. The method of synthesis, by contrast, has its foundations in previous experience and analogy. Here, the inputs are design requirements expressed as a set of features describing intentions, aesthetics, and perceptions. The path to material selection exploits knowledge of other solved problems ("product cases") that have one or more features in common with the new problem, allowing new, potential solutions to be synthesized and tested for their ability to meet the design brief.

There is a risk, in a discussion of this sort, that we lose sight of the human dimension. Owain Pedgley, in Chapter 24, reminds us that product design is essentially user-centered, with emphasis not on the study of materials as such but on the study of people and their relationship with materials. He points out that tools for computer-aided design are highly developed and universally available, but that these tools, so good at guiding the tangible aspects of a design, are as yet incapable of supporting the intangible. Web sites exist that attempt to fill this gap by providing images and brief descriptions of material collections (examples are Material ConneXion,[3] mâtério,[4] and Materia[5]), but these have not entirely succeeded. Research into more innovative approaches continues, exemplified by Ilse van Kesteren's Material

[3] www.materialconnexion.com.
[4] www.materio.com.
[5] www.materia.nl.

Perception tool, Elvin Karana's Meanings of Materials tool, Valentina Rognoli's Expressive-Sensorial Atlas and Hengfeng Zuo's Material-Aesthetic database, described in Pedgley's chapter.

This diversity of approaches carries the risk of isolation. As Kevin Edwards and Eddie Norman (Chapters 20 and 21) suggest, the differing educational paths and resulting cultures of technical and industrial designers can lead to difficulties of communication. Too much can perhaps be made of this point; the extremely successful programs at the Politecnico di Milano, at the Technical University of Delft, and at the Royal College of Art in London, among others, produce designers that are equally comfortable with both the technical and the aesthetic, a point developed further in Chapter 22 by Luigi De Nardo and Marinella Levi and in Chapter 23 by Marc de Vries. Beyond that, the success of design companies and consultancies such as Seymour Powell (London), Industrial Facility (London), Alberto Meda Industrial Design (Milan), Eek & Ruigrok BV (Eindhoven), and Artful (Ankara) impressively demonstrate the integration of technical and industrial design in successful products.

So this is a rich collection, touching on the many different aspects and influences of design, further enriched by face-to-face interviews with successful designers. I hope you will find it as rewarding as I have.

Michael Ashby
Cambridge, UK
March 2013

Preface

Our starting point for contemplating *Materials Experience* was to create a book having a composition that reflects the fundamentals for turning a design idea into a materialized outcome. There has existed for a long time an abundance of materials selection advice for designers. However, we saw that there was a human touch missing from the proceedings: a touch that would uncover not only the complex ways in which materials influence how products are embodied and how they function, but also how they affect people's experiences of products, and the complexity of materials decision making facing the designer. Let us explain a little further.

In reviewing current literature, we came across three types of material-related books used by design educators, students, and professionals. First are inspirational books that use strong imagery to showcase selected materials and their applications, serving as a kind of catalog or reference that can be quickly consulted (e.g., the "Materials for Inspiration" series by Chris Lefteri and the "Transmaterials" series by Blaine Brownell). Second are books dealing with materials selection in mechanical engineering (e.g., Ashby's "Materials Selection in Mechanical Design" and Grover's "Fundamentals of Modern Manufacturing: Materials, Processes, and Systems"). This second group comprises valuable resources on how materials can be chosen to solve technical requirements; however, they understandably do not reach into the area of how materials can be used to help realize a planned user experience. Third are books on materials selection and design, where we see an approach that is something of an integration of the first two book types. In our opinion, there has existed two widely recognized books that can be regarded as seminal texts in the field of materials selection and design falling under this third category: *The Material of Invention* by Ezio Manzini (1986) and *Materials and Design* by Mike Ashby and Kara Johnson (2002). Why did these two books leave such a positive impression on us, and why do we regard them today as still essential reading? Partly, it is the intellectual level that they present. They poke us—as designers or consumers—to think more deeply about relationships we have with the materials of our world. These two books go beyond merely a procedural matching of material properties to performance specifications, into a more troublesome but fascinating arena of personal, social, and cultural perception and experience of materials. The second reason for our fondness of these texts is their positioning within the design field. As editors, each of us has a background in industrial design; we understand firsthand the designer's desire to reach that essential balance between product function and product expression through clever or unusual material choices. We also understand that reaching such a balance requires inspiration, advice, and practical experience.

This prompted us to think deeply about how we could strengthen the materials and design arena with a new book: inspired by the seminal works of Manzini, Ashby, and Johnson, but drawing upon the wealth of new research and topics that have emerged in the last decade. It soon became clear that collectively as editors, although each of us has been active in the materials and design domain for some considerable time and completed our PhDs on the subject matter, the recent expansion of knowledge in the domain has meant that to do justice to such a book we should not work alone. So we set about defining a "wish list" of the most eminent or pioneering academics and designers in the field according to four themes we considered as fundamental to the domain: user experience, sustainability, technology, and selection. We wanted to piece together a web of authors with extraordinarily diverse competences and perspectives. The stipulation was that each author should bring a valuable contribution to explaining why, and in which ways, their field of expertise has influence not only on the materials experiences of end users of products, but also on the materials experiences and selection activities of designers.

We think we have achieved a compilation of critical new essays that provoke us to think more deeply and more widely about the materials we specify for products (as designers) and the materials used in the products that we purchase (as consumers). We have been privileged to secure contributions not only from leading academicians but also from outstanding designers. Collectively, our contributors' willingness to share their material thoughts has been remarkable. The end result is, we believe, truly a treat for our readership of, among others, design educators, design students, design researchers, and professional designers. We sincerely thank all our chapter authors and interviewee designers for their contributions.

This book could also not have been realized without the support of our institutions and staff: the Department of Design Engineering at Delft University of Technology, the Netherlands, in particular Professor Prabhu Kandachar and Professor Jo Geraedts; the Department of Industrial Design at Middle East Technical University, Turkey, in particular Professor Gülay Hasdoğan; and the Department of Chemistry, Materials and Chemical Engineering "G. Natta" at Politecnico di Milano, Italy, in particular Professor Marinella Levi.

We are indebted to Professor Mike Ashby, for so eloquently laying out the materials and design field in his Foreword and preparing our readers for the rich subject coverage they will encounter throughout the book.

Our gratitude is also owed to Steve Merken, Jeff Freeland, and their colleagues at Elsevier, for enthusiastically sharing our vision for this book and for their prompt reactions and great support at every step of the process.

Finally, our special personal thanks go to our beloved partners and families who have encouraged us throughout the book journey: Jaap Rutten, Semra-Erol-Elçin Karana; Bahar Şener-Pedgley (with Jessica and Lucas); and Yunier Virelles (with Ernesto and Camilo).

Editors
March 2013

Introduction to Materials Experience

Elvin Karana,[1] Owain Pedgley[2] and Valentina Rognoli[3]
[1]*Delft University of Technology,* [2]*Middle East Technical University,* [3]*Politecnico di Milano*

If we regard materials as "actors" playing a particular role that designers have assigned to them, as emphasized by Professor Ashby in his Foreword, then we soon begin to understand that some materials are chosen for lead roles in certain applications, while others go unnoticed as essential background actors. Deciding upon the role that a material will play within a product is one of the large challenges faced by designers. It necessarily entails a focus away from designing for product—product interactions toward designing for user—product interactions and consequent experiences. Thus, when a decision is to be made on the materials to be used in a new design, competence is needed in predicting and defining both the experiential qualities and the performance qualities of materials. Within new product development teams, it is the (industrial) designer who usually assumes responsibility to tackle "human factors" in relation to materials selection. In other words, it is the designer's remit to use materials to create particular experiences for people in particular contexts of use: to define the materials experience.

The "materials experience" (Karana et al., 2008a) refers to the experiences that people have with, and through, the materials of a product. That is, to use Desmet and Hekkert's experience framework (2007), a concern not only for aesthetic experiences provided by materials, but also for meanings that materials may evoke, and emotional responses that may originate from materials. In planning for this present book, we must admit that our initial approach was to adopt the definition of "materials experience" originally proposed by Karana in 2008. However, the expression grew conceptually much larger as we started to pool together the work of contributing authors. It became apparent that we should look to the experiences not only of *end users* of materials (through products), as mentioned, but also to the experiences of *designers* who have the initial interactions with those materials. This dual attention reflects the classic demarcation between attending to the *outcomes* of design (as particular material experiences) as well as the *processes* of design. So, with the conceptual groundwork of *materials experience* laid, we continued in our quest to define what a "designerly" perspective on material properties, materials selection and material discourse more generally would entail. We reflected on the question, "what are (and will be) the key issues affecting designers' material choices for the creation of intended user experiences?"

Manzini in his well-known work, *The Material of Invention* (1986), talked about designerly competences in materials selection, aesthetics of materials and the role of materials in shaping positive user experiences. The materials of products are often a way to lure people's initial attention, while in the longer term they can define a lasting positive or negative experience. We can be captivated by materials and

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inspired by their application; we can take great pleasure in their existence or we can be extremely put off. Thus, our internal material dialogues can be exposed to reveal ways in which materials draw us into a product or push us away. We interact with materials via our five senses. We pet the smooth surface of a ceramic vase, we tap on a wooden box and hear the vibrant sound, we watch the water drops on a glass window, we smell a new leather case, and so forth. These material–user interactions are modulated in time, across cultures and individuals, and in different contexts of use. Designers have a responsibility to consider each of these variables when taking material decisions.

The topic of materials experience has taken some time to come to prominence. As most of our readers will recognize, Ashby and Johnson (2002) made a considerable impact in the domain of materials and design. Their work helped make materials selection activities more transparent, more manageable, and more inspiring for product designers. They were the first authors we came by, who treated in an intellectual and in-depth manner the significance of the aesthetic attributes of materials for a proper materials selection in product design. Besides the general, technical, and ecoattributes, they added aesthetic attributes of materials into the material properties list for designers. In their definition, aesthetic attributes originate from the sensorial properties of materials, such as warmth, softness, appearance, and so forth. Additionally, Ashby and Johnson reinforced the two overlapping roles that materials play in product design: providing technical functionality while creating product personality. Accordingly, they pointed out that intangible issues such as perceptions and intentions (of the designer) should take a role in the materials selection activity for products. Since the publication of Ashby and Johnson's book, the number of research studies concerning material interactions and product design (covering sensorial properties, attribution of meanings, and elicitation of emotions) has grown considerably. Important contributions have been made by, for example, Zuo et al. (2001), Rognoli (2004), Miodownik (2007), Karana et al. (2009), Van Kesteren (2008), Rognoli (2010), and Karana (2009).

In a study conducted prior to the emergence of "materials experience" (Karana et al., 2008b), a review was made of pioneer books concerned with materials selection. The review covered both industrial design and mechanical design, and included books published between 1967 and 2005. We were able to track the variety of topics and emerging issues throughout the years, one of which was "sustainability". Interestingly, in most of the pre-1996 sources, environmental (and later on "sustainability") issues were placed at the bottom of listed material requirements for designers and engineers to take into account. However, only a few years later, Mangonon (1999) organized material selection factors under three main topics: property profile, processing profile, and environmental profile. He emphasized that selection based on an environmental profile covers multiple impacts of a material: its inherent properties, its manufacture, its use, its reuse, and its disposal. Today, we see these collective impacts under the wider umbrella of sustainability, with their recommended consideration moved considerably further up from the bottom of materials selection criteria.

In parallel to the concerns of sustainability, technological advancement of materials, for example, having superior properties such as conductivity, sensing, thermal stability, and mechanical resistance, as well as significant improvements in additive manufacturing, has been essential for product development and has affected designers' material decisions. These technological developments inevitably influence (or will influence) how we—as users—experience materials, and how we—as designers—create materials experiences. Manzini (1986) emphasized that technologies in the mid-1980s were radically altering the meanings that once endowed materials with cultural and physical depth. Having witnessed three further decades of technological development, there can be no doubt that our everyday experiences of materials are more diverse than ever, and that the designer's opportunity to build meanings into products through materials is wider but more complex.

If we survey the field of materials and design in 2013, we can see exciting new developments in relation to the fundamental issues, which for the purposes of this book we have collated under three themes: "Touched by Materials" (user experience), "Living with Materials" (sustainability), and "Futures through Materials" (technology). Some of the captivating developments under these three issues are the emergence of evidence-based materials selection for product personality and expression; the functional opportunities of nanotechnologies; the imperative to consume less material, use existing resources more wisely, and design for graceful aging; and the increasing discretion and knowledge of end users seeking pleasurable and memorable experiences from products. These fundamental issues are shaping, and will continue to shape, our future materiality. Our fourth and final book theme, "Proficiency in Materials" (selection), is essentially transitory—referring to the practical issue of choosing one material over another, gaining the basic necessary grounding to make sound material decisions, while taking into account the influence of issues arising from the preceding three themes.

In Section 1, Touched by Materials, we focus on the fundamentals of user experience, that is, how people approach to materials, how they sense them, how they attribute meanings to them, and how they love or hate them. Pioneers in the domain offer chapters on the role of materials in product experience, sensory pleasure, multisensory approaches that bring about positive (or negative) materials experience, universal and cultural meanings in relation to material aesthetics, sensoaesthetics of materials focusing on sound and taste, and different (cultural) design approaches in transferring material meanings. The last chapter of this section, with its particular focus on ethical issues in material decisions concerning our future of living, serves as a bridge to the next section, Living with Materials.

In Section 2, Living with Materials, we present contributions that discuss materials and design in relation to sustainability. The section covers the roles of materials in achieving social sustainability, "emotionally" durable design, and alternative design approaches including designing with waste and design for imperfection and graceful aging. The last chapter of this section presents a number of novel multipurpose materials with good environmental credentials and brings us to the next section, where we discuss novel approaches and technologies in the materials and design world.

Section 3, Futures through Materials, brings together chapters concerned with technological developments in materials and manufacturing. Fundamental "technology-driven" issues discussed in the materials and design domain are covered, alongside their effects on our daily experiences with materials and products. Lightweight design, for example, presents a new approach to design thinking and the selection of materials and shaping processes. The design potential of new generations of smart, reactive, and multipurpose materials are discussed, as are nanomaterials and bioinspired materials (biomimetics).

The chapters under these three themes are heavily intertwined, thus it was in some cases challenging to place a particular chapter under a particular theme—essentially reinforcing the point that the three themes fundamentally affect each other, designers' material choices, and ultimately our materials experiences. The integral consideration of user experience, sustainability, and technology is essential for teaching and practicing materials selection and design. Accordingly, in Section 4, Proficiency in Materials, we present contributions concerned with the practical task of choosing one material over another. The chapters include diverse topics including balancing functionality and expression through materials, ways of learning about material properties, and the development of new experiential-based materials selection tools and methods that can complement well-established technical-based selection.

In between the four main sections of *Materials Experience* you will find the results of interviews with eight internationally renowned designers from the countries we as editors are associated with (Italy, the Netherlands, Turkey, and the United Kingdom). Each designer communicates a material dialogue in relation to the processes and outcomes of their design activity. In other words, these invited designers kindly divulged their thoughts on how they go about selecting materials, the influence of the book themes on their work, and the anticipated materials experience of the end users to whom they are targeting their created products. Within these material dialogues it is easy to detect the high regard that designers have for careful material use. All the subjects covered in *Materials Experience* collide in the designers' studios and workshops.

Having immersed ourselves in the chapters and interviews contained in *Materials Experience*, we indulged ourselves somewhat and asked "what would be *our* choices to present herein, as remarkable cases of materials experience, focusing on one or more of the book themes?" We selected six product examples to share with our readers, as a taster for the kinds of keywords and discussions that permeate throughout the book. For each of the six products, there could easily be another six, and then another six. But we included some personal favorites to illustrate in a very direct way the subjectivity of material appraisals and the very personal nature of materials experience.

Valentina's first example is the "Frida" chair by Odoardo Fioravanti (Figure 1).

FIGURE 1 "Frida" chair by Odoardo Fioravanti for Pedrali, 2008 (www.pedrali.it). *Photo by Leo Torri.*

It is a traditional material (oak and plywood), which is embodied in an unconventional design with a very thin structure and a strong resistance. The thin plywood shell is shaped using 3D veneered technology. The designer has used a new veneering technique that allows the creation of challenging shapes with thin surfaces. This is the very first chair made that marries this kind of thin veneer with a solid wood structure. It is a good example of how a new 'technology' (in this case a manufacturing technology) triggers a unique material experience. It is elegant, simple, and a sculptural beauty – and also extremely lightweight at only 2.7 kg.

Valentina's second example is the "Biscuit" table, with which the designer Patricia Urquiola earned the best marble designer award in 2010 (Figure 2).

FIGURE 2 "Biscuit" table by Patricia Urquiola for Budri, 2010 (www.budri.com).

It is produced from a very well-known material, marble, but in a very innovative way to create a unique sensory experience, especially to gratify vision. The designer has played with transparency, to create a translucent material rather than be satisfied with a conventional opaque appearance. This is quite a surprise to anyone who interacts with the table.

Elvin's first example is the "Setu" chair designed by "Studio 7.5" from Germany for Herman Miller (Figure 3).

Setu is an example of how materials embark upon—or even create—an excellent user experience when they are considered thoroughly alongside process-shape-function and use. The materials used are not extravagant, for example polypropylene – a commodity thermoplastic – is used for the spine. However, the kinematic function of the spine works properly because of the mechanical properties of polypropylene. When you sit on the chair, the textile material touches you elegantly, softly; it envelops you gently. And the alloy base of the chair makes a great contrast with the light feather feeling of the seat: robust and durable. The designers have taken the principle of 'honesty

FIGURE 3 Setu Multi-purpose Chair by Herman Miller (www.hermanmiller.com).

in materials' as a key component in their design, avoiding the use of any kind of toxic coatings. Setu is 93% recyclable. The final result is environmentally sensitive, elegant, and truly comfortable: a life-long chair with a well-considered material-shape-process combination.

The second example of Elvin is the "Plattan" headphones by Urbanears (Figure 4).

This product exemplifies the combination of multiple materials in a sensible way, which is a great challenge for industrial designers. As a company, Urbanears aims to create headphones that are experienced rather like clothes, with a combination of utility and semantics heavily influenced by

FIGURE 4 "Plattan" headphones by Urbanears. © *2013 Jaap Rutten.*

> material choices. Material combinations are a main characteristic of the product: they select velvet-like plastics that are complementary to the soft leather cushioning and textile 'heading'. Another challenge is that each of the different materials has the same colour, yet the product still appears balanced and of high quality.

Owain's first example is the "Stretch" pot stand by Joseph Joseph (Figure 5).

> This handy kitchen utensil is a great application of co-injection moulding. A rigid thermoplastic core provides the structure, while a thermoplastic elastomer is used on the outer surfaces for its high temperature resistance and non-slip properties. As a collapsible lattice with fluorescent coloring and rubberized texture, 'Stretch' is irresistible to interact with! It is also functionally superb – able to support very small pots through to large baking trays.

The second example of Owain is the "RA1" acoustic guitar by Rob Armstrong, developed in collaboration with Cool Acoustics (Figure 6).

> I have been privileged to work with some great guitar makers during my involvement with the Cool Acoustics project to develop technology and know-how for instruments made from synthetic alternatives to spruce, cedar, mahogany etc. This particular prototype, constructed mostly from foamed polycarbonate and plywood, emphatically defies people's reservations about plastics and musical instruments. It sounds stunning and plays beautifully. In blind tests people can't tell it apart from an expensive wooden guitar. If one of the designer's responsibilities is to push product design, innovation and differentiation through materials, then I think this product is a perfect example.

FIGURE 5
"Stretch" pot stand by Joseph Joseph. © *2013 Owain Pedgley.*

FIGURE 6
"RA1" acoustic guitar by Rob Armstrong/Cool Acoustics. © *2003 Cool Acoustics.*

So much has been done and discussed in the materials and design domain in the last decade, some of which has found its place in design practice and design education, while some has yet to come to the fore and remains at a level of noteworthy points to be considered for the future of our society and material possessions. We aim to present a panorama of completed works and on-going discussions that are shaping, and will continue to shape, our materiality, our selection of materials, our understanding of products, and our materials experience. What has occupied the materials and design domain in the last decade that should be transferred to design education and to the professional practice of design?

In conclusion, our hope is that on reading *Materials Experience* you will be left challenged yet energized to bring a principally human-centered perspective to the materials decisions you take in future design projects, or to the materials and design curricula you may develop for future generations of designers, or to the appraisals you make when encountering new products.

Now, go experience!

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SECTION 1

Touched by Materials

This section focuses on user–material interactions and the experiences that result from those interactions. The contributing authors explore how people approach to materials, how they sense them, how they attribute meanings to them, and how they build deeper relationships with them.

CHAPTER 1

Designing Material Experience

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CONTENTS

> More than half of the world's population lives in city centres. This is putting an increasingly heavy burden on traditional means of inner city transport. We believe this asks for a new and fresh approach to inner city mobility. We are a young ambitious Dutch company that originated out of love for bicycles and hunger for change.
>
> At VANMOOF we pursue only one goal: help the ambitious city dweller worldwide move around town fast, confident and in style. We stripped the traditional Dutch bike from redundant hoo-ha, that can only break or frustrate, and added sensibility instead. The result? Simplistic striking bikes so smooth that they fit your style demands, yet so functional they make you go to work whistling. The no-nonsense VANMOOF bike is the ultimate urban commuter tool, anywhere around the globe. Be aware "cause we shake the unshakable"!

Both quotes are taken from the Web site of Van Moof (2012), a Dutch bike manufacturer. The first quote describes the future world of biking, as seen by the company, and the second, Van Moof's brand identity. Together they shape the context underlying the design (the "why") that boils down to the fictitious (mission) statement: "VANMOOF wants to fuel the ambition of commuters and make them 'go to work whistling'".

In the second quote, this goal is translated into an intended user experience (the "how") and the qualities of a subsequent bike design (the "what"; Hekkert and van Dijk, 2011). At the user experience

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level, the level that follows immediately from the context, the company promises to make you move around town *fast*, *confident* and *in style*. These qualities describe the interaction between a (future) user and the to-be-designed bike; they indicate how users will (or should) experience the bike. From these interaction qualities, the product qualities can be derived. In order to facilitate fast, stylish, and confident driving, the bike has to be nonredundant, simple, sensible, smooth, and no-nonsense.

This short example of experience-driven design by following a why—how—what model makes perfect sense and allows a designer to define up front what the product must do and express (what) in order to attain a desired user or product experience (how). Both are firmly rooted in a (future) world, a world that is viewed and shaped by the designer in order to decide what experiential and/or behavioral effects the product will have on people (why).

Now that a vision on the new bike is defined, the next design stage can take place: how to implement these product and interaction qualities in the design of a bike. The quoted paragraphs only suggest removing all nonessentials from a normal bike, a step toward this goal—"we stripped the traditional Dutch bike from redundant hoo-ha". But if we look carefully at the result, the VANMOOF bike (Figure 1.1), we could identify some further design decisions that support the intended user experience in the indicated way.

The bike has no visible extras; it looks very simple and basic. Its aluminum color adds to the impression of smoothness and no-nonsense. Significantly, and giving the bike its distinctive, stylish look, the lights are integrated in the top tube, in such a way that they allow for confident riding in the dark. The bikes are equipped with a Dutch-style kickback brake, further adding to the clean outlook. With so little visual noise and bulb, the bike affords fast and confident driving. The thick wide wheels make riding on and off pavements and obstacles problem free. The broad handlebar and durable Schwalbe tires top-off the smooth no-nonsense look. Maybe most importantly, the VANMOOF has a striking aluminum rust-free frame, a lightweight material that facilitates speedy riding.

From this brief analysis, we can see that the intended user experience has consequences for the product's technology (e.g., in-built lighting), form (e.g., top tube), color, and material selection: the material of the frame, tires, and brakes all significantly contribute to a fast, stylish, and confident driving experience. Apparently and intuitively, the VANMOOF designers did the right thing and materialized the

FIGURE 1.1
Standard VANMOOF bike. *Courtesy of VANMOOF.*

intended experience. To make such a process more deliberate, the question that will be addressed in the remainder of this chapter is "Can we design a material experience?"

FROM PRODUCT TO MATERIAL EXPERIENCE

Over the past years, we have seen a steady stream of publications reporting ways to capture and analyze "user experience" (e.g., Hassenzahl, 2011; Law et al., 2009) or "product experience" (e.g., Desmet and Hekkert, 2007; Schifferstein and Hekkert, 2008). Despite failed attempts to adequately define the two concepts, both refer to a similar phenomenon and their advocates seem to agree on the following characteristics:

1. *Experiences are inherently subjective*. Experiences take place in (the mind and heart of) the user and only he or she has access to the felt quality of this experience. This does not automatically imply that the user can always correctly recall and/or report experiences. Experiences are notoriously difficult to verbalize. Even more difficult for users is to correctly identify where experiences come from and what their causes are (e.g., Wilson, 2002). For that reason, we have seen an accumulation of sophisticated methods to capture and scrutinize experiences (e.g., experience sampling, Larson and Csikszentmihalyi, 1983; Day Reconstruction Method (DRM), Kahneman et al., 2004).
2. *Product (or user) experiences arise in interaction with a product.* By definition, product experiences refer to those experiences that are evoked by interacting with a product. They may result from actual use (hence, user experience), but could also be evoked by simply anticipating usage or thinking about a product (see Desmet and Hekkert, 2007). The product, with all of its properties, thus plays a main part in this process. When the product is an interactive device, we typically speak of user experiences.
3. *Experiences are affected by personal and situational factors.* Because of their subjective nature, experiences are determined by the mind(set) of the user, his or her goals, expectations, dreams, and desires. Also, experiences are heavily influenced by the context of use. That glass of Raki on the sunlit terrace during a holiday in Turkey tastes completely different from a similar glass 2 weeks later at home in the gray and cold Netherlands.
4. *Experiences develop or change over time.* During the episode of using a product—say, making a cup of espresso with your new machine—the experience will not be constant and similar over the full 45 s (e.g., Laurans et al., 2012). Product properties you are dealing with change over time, and so may your mood or expectations in response to the product. Accordingly, experiences may easily differ at different moments of use over time (e.g., Karapanos et al., 2010).

Types of experience

We may feel confident on our bike, astonished over the power of our new laptop, relieved to see the old record player still works, get frightened by the smoke coming out of our toaster, and proud to own a Tag Heuer watch. Product experiences come in many kinds and types. Some experiences are pleasant and companies (should) certainly make an effort to design for these and avoid unpleasant ones (Jordan, 2000). Or should they? Recently, design researchers have started to explore the relative benefit of unpleasant experiences in achieving our goals (e.g., Fokkinga and Desmet, 2012). Some talk of sensory experiences and, thereby, implicitly suggest that other experiences do not require sense perception, but may be merely cognitive.

The, so far, most sensible—admittedly, we are biased—distinction as to different types of experiences was proposed by us (Desmet and Hekkert, 2007; Schifferstein and Hekkert, 2008). It is defendable to speak of an aesthetic experience, an experience of meaning, and an emotional experience. Where the aesthetic experience involves the degree to which an object delights our senses, an emotional experience arises from goal attainment (e.g., happy) or violation (e.g., sad). The experience of meaning is all about attributing characteristics to objects, such as smooth, usable, or feminine. These three types of experience often appear as three components of a single experience, and may therefore be hard to separate while actually engaged in the experience. Moreover, they are clearly related and affect each other's quality (e.g., Desmet and Hekkert, 2007). Nevertheless, as to their underlying process, they can be conceptually separated.

Next, we will explain more in depth the underlying processes that result in each of the three types of experience. These processes not only explain why (and when) we have a particular experience, they also predict when such experiences are most likely to be universal—everybody will pretty much have the same experience—and when (groups of) people, such as different cultures, will have different experiences. It is our firm belief that one can only meaningfully talk about cultural or individual differences when one understands the psychological mechanism that is rooted in human nature and that may (occasionally) lead to universal agreement. Although the mechanisms are—obviously—generic and not specific for our interaction with objects, we will limit ourselves as much as possible to the way materials and material properties can lead to these experiences. When considering material experiences, we believe "the experience of meaning" is the most relevant category and this type of meaning will therefore be treated more extensively in Section Meanings of Materials.

Material aesthetics

Elsewhere, we have argued that there are good reasons to restrict the term aesthetic to the *pleasure attained from sensory perception* (Hekkert, 2006; Hekkert and Leder, 2008). Defined in this way, anything can be appreciated aesthetically, an artwork, a product, a landscape, an event, or even an idea. Needless to stress, materials can also be aesthetically pleasing.

Crucial to understanding why we like to see or touch something is to look at the evolutionary benefit of liking something (see Hekkert, 2006; Ramachandran and Hirstein, 1999, for similar views). Simply put, we like to look at (or feel, or listen to) things that are good for us. The main task of our sensory systems, including our brain, is to make sense of the world, to identify things, to navigate around, in sum, to create order in a chaotic environment. For that reason, we have "learned" to aesthetically appreciate those features, cues, or patterns that facilitate these functions.

Various aesthetic principles can be derived from this line of thought (see Hekkert, 2006) and we will now briefly discuss two of these and apply them to material aesthetics. First, we like to invest a minimal amount of means, such as effort, resources, or brain capacity, to attain the highest possible effect, in terms of survival, learning, or explaining: the principle of maximum effect for minimum means. From this, it could easily be predicted that products should minimize the amount of material used, while preserving the effect aimed for. Waste of material is not only undesirable from a sustainability point of view.

A second aesthetic principle that may affect material selection is the principle of most advanced, yet acceptable (Hekkert et al., 2003). People prefer products that are on the one hand maximally novel while being as familiar as possible. While the latter is most easily achieved by sticking to a well-known shape, novelty could very well be attained by a new material application (see, for example, "Soft Vase" by Hella Jongerius elsewhere in this book). Note that this novelty is a subjective and a relative assessment. First, what is regarded as novel depends, for instance, on your previous experiences with similar products and/or materials. Second, the material may be very novel for the product at hand, e.g., cork applied in an interactive device, but not in an absolute sense. Correspondingly, if you decide on a very novel shape, you may be well advised—from an aesthetic point of view—to stick to a familiar material for the product category.

Emotions to materials

There is wide consensus that an appraisal model most accurately describes the process underlying our emotional response (e.g., Frijda, 1986; Scherer et al., 2001; Ortony et al., 1988), also to products (Desmet, 2008). According to these appraisal theorists, an emotion is elicited by an evaluation (appraisal) of an event or situation as potentially beneficial or harmful to a person's concerns. For example, on seeing the new Renault Dezir, a person is expected to experience desire because it feeds his or her concern of being admired. An important implication of appraisal theory is that it is the interpretation of the object, rather than the object itself, which causes the emotion. Only when people share this interpretation and have the same concern, people will experience a similar emotion: we all experience fear when a gun is pointed at our head since we all interpret a gun as life threatening and share the concern of staying alive. Often, however, people differ as to the concerns they bring into a situation and interpret products very differently.

Just as a product, materials can also evoke emotions. One can be fascinated by the strength of a carbon fiber composite in a chair with an extremely thin surface thickness (Figure 1.2). One can also be disappointed over the easily scratched surface of a polypropylene lunch box or feel disgust toward the greasy touch of a rubber handle (Sonneveld, 2007). An interesting emotion to evoke by materials is surprise. Materials can be surprisingly light or heavy, smooth or rough, warm or cold, relative to

FIGURE 1.2

Manta chair made of carbon fiber, by Robby Cantarutti. *Courtesy of Mast Elements.*

previous encounters or expectations built upon visual inspection (see Ludden et al., 2008, 2009). As a result, the user is surprised to touch or lift the product and when this experience (of lightness, for example) is better or more appropriate then expected, a positive emotion such as relief, amusement, or happiness is to follow.

MEANINGS OF MATERIALS

We often and easily ascribe a character or meaning to a product and its material: these sneakers look *cool*, this glass is *fragile*, this plastic cover feels *artificial*, and this car seat is very *comfortable*. Just by looking at these examples, there are a couple of interesting observations to make. First, it is often very difficult to separate the meaning of a material from the meaning of the product in which the material is embedded. Are the sneakers cool because of the material used or despite its material? And is the material considered cool because of the sneakers? Second, product and material meanings are rooted in our sensory perception. The sneakers *look* cool and the plastic cover *feels* artificial.

The second observation also brings us to the third, and most important one: strictly speaking, materials do not possess a meaning (Hekkert and van Dijk, 2011). Just like our emotions and aesthetic responses, material or product meanings arise in interaction and are context sensitive (Karana, 2009; Karana et al., 2010). Although some material meanings may *appear* as a property or can be colloquially considered an intrinsic character of a material (e.g., wood is warm), and we will argue in Section Universal meanings why this is, they in fact are not. Meanings are attributes or labels, qualities assigned to products and materials and, theoretically, any material can inherit any meaning in a particular context. Nevertheless, there are patterns or regularities in material-meaning relationships (Karana and Hekkert, 2010). A material, for instance, may express professionalism when it is smooth and dark (colored), when it is used in an office environment and when certain technical properties are combined for enhancing its function (e.g., combining strength and lightness). Such material-meaning associations may be near universal because they are rooted in sensorimotor experiences (Section Universal meanings) or they result from learned conventions (Section Learned meanings) leading to less "stable" relationships and cultural/individual diversity.

Universal meanings

Some figurative qualities are attributed to things, and presumably materials, by means of embodied metaphors or "embodied projection" (cf. Van Rompay, 2008, for an overview). This process refers to theorizing in the field of cognitive science about the role of our body in understanding our world, and the concepts we have invented to describe our interaction with it. Warm temperatures are more pleasant than cold ones and so we see *a warm person* (or thing) as more *inviting* and *open*. If things get uncomfortably hot we tend to sense tension, as in *a heated debate*. Similarly, when someone is *down*, the expression refers to being emotionally *low*, and we are mentally *unstable* when we are psychologically *out of balance*. As many scholars in cognitive linguistics and embodied cognition have shown (e.g., Gibbs, 2006; Johnson, 2007; Lakoff and Johnson, 1980; Pinker, 2007), these spatial-relational references rooted in bodily experience are omnipresent in our daily language and concept formation. As we have shown elsewhere, they also allow us to explain and design the expressive character of objects (Van Rompay et al., 2005).

From this, we could easily predict why some materials appear to have designated, embodied meanings. Wood is literally warm to the touch and therefore perceived as *inviting* and *cozy*, whereas stone or steel are generally cold to the touch and thus tend to be perceived as more *distant*. These latter materials are, on the other hand, relatively heavy and would for that reason also be regarded as *high quality*. Similarly, light materials have a tendency to be considered *cheap*. Next, when a material is rough, people will perceive it as more *natural* than when it is smooth, and transparent materials are most likely, or should we say naturally, seen as *fragile*. Finally, soft materials are mostly regarded as being *alive* where hard materials are considered *dead*. Such material-meaning associations are, by their sensorimotor nature, very robust and persistent and not very sensitive to cultural or individual differences. Yet, for many new materials, with a much shorter history than, for example, wood or steel, the meanings still have to be learned. Also, some "cultural" meanings, which are not rooted in sensorimotor experience, such as "toylike", "modern", or "cool", must be learned through the kind of associative processes that will be discussed next.

Learned meanings

When a material is frequently used in a certain context, it becomes associated with particular meanings that are, for whatever reasons, dominant in that context. These meanings may, over time, act as if they are intrinsic characteristics of that material. Although ceramics may univocally be considered of *high quality* because of that material's rigidity and weight (see Section Universal meanings), its frequent use in expensive, long-lasting dinnerware, for instance, has certainly reinforced the attribution of this meaning to this material. Likewise, a leather and plywood combination in home/office furniture—which dominated the 1950s' lounge chair designs (e.g., Eames' Lounge chair & Ottoman)—is (still) appraised as *elegant*, *rich*, and *businesslike*. We have learned to attach these meanings to these materials, and one can dispute the extent to which intrinsic properties are responsible or whether the attribution is more or less arbitrary.

Hekkert and van Dijk (2011) emphasize that the user-product relationship is part of a larger context that consists of all kinds of factors, e.g., social patterns, technological possibilities, and cultural expressions, which affect the way people perceive, use, experience, respond, and relate to products. The effects of these contextual factors on the interaction are mediated by the concerns of the user in terms of goals ("what we want"), standards ("how we believe things ought to be"), or taste ("what we like") (Ortony et al., 1988). For example, Cleminshaw (1989) in his book *Design in Plastics* quoted Kenji Ekuan, a famous Japanese industrial designer, who explained that Japanese people had so entirely based their sensitivities upon the transience of time that they even project this approach on every aspect of their life, including materials. So, they not only feel uncomfortable with, but they even hold a horror of plastics that deny death.

Many material-meaning associations are learned within societies based mainly on the frequent use of a material in a particular context, its ease of formability, its utility function, etc., such that there will inevitably be variations in material-meaning associations between cultures. The results of a study conducted with Turkish participants revealed metal to be regarded as formal and less domestic compared to wood and ceramics (Karana, 2004). The Turkish participants associated metal with factory environments and mass production explaining that they would not choose metal for their kitchen interiors. In another study where we compared Chinese and Dutch people (Karana and Hekkert, 2010) in terms of their appreciation of plastic and metal products, we could show that these two cultures show significant differences in their valuation of metal and plastic products. Contrary to the Dutch participants, the Chinese valued plastic products more than metal ones by explaining that plastic is "more attractive" and "elegant". There might be a number of motivations behind their appraisals. For instance, one might explain this by the fact that people from Asian cultures are generally fond of natural and organic forms, which are mainly associated with plastics. It may also be partly explained by an expanding number of plastic products in Asian markets, which make Asian people more familiar with this material family. These various cultural studies underline how material selection across worldwide markets must be treated sensitively, and how difficult it can be to reach a single definable "global material experience" from a product.

How meanings change

Improvements in manufacturing technologies and materials science have stimulated new materials and forms in product design. An example is the Plopp stool, designed by Oscar Zieta. It is composed of two ultrathin steel plates cut into the desired shape and welded around the edges. Then air under high pressure is shot into the unit causing an expansion into the desired form. This results in a surprising material-form match that is not common to see in metal products. It looks soft and warm from a distance—just like a vinyl inflatable toy—but is found to be hard and cold when touched. The metal of the Plopp stool can certainly be evaluated as friendly and cozy, maybe even toylike, which are different meanings than those traditionally assigned to metal (i.e., cold, aloof, etc.).

Another example is the changing image of plastics in time. Many new kinds of plastics have emerged in the last decade. Each has different properties and is used in a variety of products. When plastics first emerged, they stood for cheapness, low quality, and inauthenticity (Sparke, 1990) and their tactile experience was generally unsatisfactory for people (Walker, 1989). They were toxic and perceived as not appropriate for hygienic uses. Now plastics are widely used in countless high-quality products, and are prevalent even in medical appliances requiring nontoxicity and outstanding hygiene. A recent design from Lana Agiyan perfectly illustrates this altered status of plastics. It is a vacuum-thermoformed and blow-molded acrylic baby cradle: Bubble Baby (Figure 1.3). The following is a quote from the Design42Day Web site (Design42Day, 2012) on how the materials of the product are described:

> One of the most fascinating features of the cradle is its innovative nano tech coating, which was developed together with an Estonian factory and prevents the plastic from potential scratches. Due to the treated surface, the crib obtains improved optical transparency, repels dirt and can be cleaned easily just by using a dry piece of old cloth without the use of chemical detergents. Due to the photocatalytic effect of the nano particles of titanium dioxide, contained in the liquid polymer base, the coating degrades dirt as well as air pollution when it is exposed to sunlight. In other words, strong light starts the ionization effect and therefore acts self-cleaning and at the same time "heals" potential unhygienic scratches. The coating is absolutely safe for children, eco-friendly and even certified for the EU.

This example shows how advanced material technologies change the application of a certain material for particular domains. Plastics, yesterday's toxic material, are today applied to baby cradles for being an extremely hygienic, safe, and self-cleaning material.

FIGURE 1.3
Bubble Baby, by Lana Agiyan. *Courtesy of Lana Agiyan, photo by Eugen Zahoroshko.*

In brief, some meanings tied to a material have loosened because of technological advances. Histories of materials are shifting. The meanings attributed to plastics in 20 years by someone whose first experience with plastics will be through his/her Bubble Baby will certainly be different from what plastics mean to those of us still in possession of a Bakelite radio.

DESIGNING MATERIAL EXPERIENCE

We ended the first section with the main question driving this chapter: can we design a material experience? If the experience we aim for can rely on universal patterns, it is obvious we can. For example, it is safe to predict that everyone will perceive the lightweight VANMOOF bike as *flexible* and its smooth surface as relatively *clean*. These qualities will probably even hold when we change the context, and apply the same material properties in the design of another product, such as a baby stroller. Other (components of the) experiences, however, are more prone to cultural or individual differences as to learned traditions, background, and personal concerns. Here, designers could rely on segmentation; the VANMOOF bike may look cool to Western commuters, but not to Indian farmers. Also, the product and the communication around it, i.e., marketing, can help to bring people into the right mind-set, to ensure they look at the product similarly, and have the same expectations and background knowledge.

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Sensing Materials: Exploring the Building Blocks for Experiential Design

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CONTENTS

People use all their senses in order to explore the world surrounding them. For instance, in a city environment people look around to orient themselves, they observe the people and objects they meet on their way, they feel the difference in materials when they cross streets and walk on sideways, they may incidentally touch objects or people on their path, they hear sounds from traffic and phones ringing, and they smell the exhaust from cars, the air in the subway, and the fresh bread from a bakery shop. In this highly complex environment, all the senses perceive information that may be relevant to a person. However, it can be difficult to distill an overall impression out of this abundance of information, since these sensory impressions originate from many different sources

If we limit ourselves to the case of a single product, the situation becomes less complex. Nonetheless, even for a single product multiple sensory modalities tend to be stimulated when a person interacts with it (e.g., Schifferstein, 2006). Since there is now only a single source of stimulation, the brain typically tries to integrate all the incoming sensory information to create a unified, holistic product experience. Various studies have suggested that the greater the number of sensory modalities that are stimulated at any one time, the richer the subjective experiences will be (e.g., Bahrick and Lickliter,

Materials Experience. http://dx.doi.org/10.1016/B978-0-08-099359-1.00002-3

2000; Stein and Meredith, 1993). In addition, when people interact with products, they may experience a number of different events over time. For instance, when people use a hair dryer, they pick it up, feel its weight and shape, and switch it on. Then they hear the motor sound, feel a current of air growing stronger and heating up. They move the hair dryer in different positions to dry the hair from different angles, and they hear the sound changing during their movements. In addition, they may perceive the smell of the heated motor and its container. Hence, whenever people use a product, they typically perform actions on (or with) that product and their senses provide feedback regarding how the product or the environment reacts to those actions.

Designers can develop a scenario of the sensory events that occur when a person encounters a product and may use this scenario as the starting point for the design of a new product (MacDonald, 2002). Considering multiple sensory modalities during the design process is likely to create richer, more interesting and more engaging user–product interactions (e.g., Schifferstein and Desmet, 2007; Schifferstein, 2011), because these products exploit the full potential of people's sensory connections with the surrounding world (Howes, 2005). Therefore, it is important for designers to know what kind of actions people will perform with a product, how they will perceive it during these interactions, and how the consumer's senses work together to deliver rich and varied multisensory experiences. Despite the important role the senses play in a person's interactions with the environment, very few industrial companies have attempted to make full use of the multisensory potential of the products they market (see Hine, 1995; Lindstrom, 2005).

Only when a designer chooses the materials for a product, the design really comes to life. What was previously a concept, a description, a two-dimensional sketch, or a three-dimensional virtual rendering, now becomes a three-dimensional object. It takes up space in the real world, it has a feel and a heaviness or lightness, it interacts with the light and its surroundings, it has a specific smell, and it makes particular sounds when tapping, moving, or rubbing it. Hence, choosing materials for a design makes it perceptible through multiple sensory modalities; it can seduce people to interact with it, and helps to create an engaging and memorable experience.

RELATING SENSORY PERCEPTION TO MATERIAL PROPERTIES

Product characteristics that are perceived through the sensory modalities largely find their origin in the properties of materials. While the visual impression of a material includes the surface colors, glossiness, and patterning, the tactile impression includes an object's weight, its coldness or warmth, and the surface's hardness, softness, and elasticity. In addition, both these senses may perceive surface texture characteristics, such as roughness and waviness. The auditory modality can perceive sounds emitted by a material, as well as the material's acoustical response to surrounding sounds. Smell (and taste) impressions depend on perceiving the molecules in the material.

Material properties can be subdivided into intrinsic and extrinsic material properties (Addington and Schodek, 2005; Fernandez, 2006). Intrinsic properties are inherent to the material and do not change under steady state environmental conditions. Examples of intrinsic material properties include mechanical properties (e.g., strength, modulus of elasticity, toughness), physical properties (e.g., density), and thermal properties (e.g., conductivity, specific heat).

Extrinsic properties are independent of the material's atomic or molecular structure, but are defined by the material's macrostructure. For instance, when materials are molded into the right shape for application in a product, their weight, acoustic properties, and flexibility might change. In addition, specific surface treatments like polishing, painting, and varnishing affect the color, reflectivity, and surface texture of the material. Furthermore, these treatments influence the material's response to environmental sounds, and the sounds perceived while tapping or scratching the object. The way in which materials are combined and the way in which different elements are connected will also impact their perception. Additionally, extrinsic properties are dependent on the environment: the color of a material is, for instance, also determined by the spectral distribution of the incident light and, in some cases, by the surrounding temperature (Addington and Schodek, 2005).

Many material properties can be measured with established and often standardized procedures using instrumental methods. Some perceived sensory attributes are closely correlated with these instrumental measures (e.g., Rognoli, 2010). Color perception can, for example, be measured according to the CIE $L^*a^*b^*$ color coordinates proposed by the International Commission on Illumination (CIE). Analogously, tactile warmth is closely related to the contact temperature, which is determined by the density, the thermal conductivity, the specific heat, and the temperature of the material (e.g., Bergman Tiest and Kappers, 2008; Obata et al., 2005). For many sensory attributes, however, researchers have not yet established a clear relationship with objective measures. For instance, although tactile softness is correlated to the technical attributes Young's modulus and surface hardness (Ashby and Johnson, 2002), none of the current measuring methods or models can accurately describe a material's perceived softness.

THE SEPARATE ROLES OF THE SENSORY MODALITIES IN MATERIAL EXPERIENCE

The way in which people perceive information varies among the senses. The sensory receptors of the different modalities respond to different forms of stimulation: electromagnetic radiation for vision, vibration of air molecules for audition, mechanical pressure and temperature changes for touch, volatile substances for smell, and water-soluble substances for the sense of taste (Coren et al., 1994). Some types of sensory inputs require or benefit from motor actions (eye movements, head movements, hand movements, sniffing, tongue movements, and slurping) and as such the exact motor actions often depend on the type of assessment the person is trying to make (Lederman and Klatzky, 1987). Because each sensory modality may be considered as a separate information channel, the modalities often receive different types and amounts of information when a product is experienced.

Product experiences are based on all of the incoming sensory information, no matter whether a person perceives it consciously or not. Schifferstein and Cleiren (2005) investigated the similarities and differences between the roles of the various senses in modulating our multisensory product experiences. They presented participants with six simple products and choreographed the active interaction between user and product in equivalent ways for four modalities. Vision and touch turned out to be approximately equally successful in providing participants with detailed information concerning a product; audition proved somewhat less useful, and olfaction provided the least detailed information.

Furthermore, products perceived by vision and touch were found to be the easiest to identify and yielded the clearest memories of previous events and associations to persons and other products.

In a complimentary experimental study, Schifferstein and Desmet (2007) assessed the roles of the various senses on people's perception of different everyday products by comparing the effects of blocking one modality. They found that preventing people from seeing the products had the most detrimental effect on the amount of functional product information that they perceived. Interestingly, when products cannot be seen, people report that their experiences become more intense and that they start to use their other senses more. When tactual perception was blocked, an emotional dimension of tactual product experiences was revealed: familiar products felt strange as they lost familiarity. It seems as if through blocking tactual perception one becomes somewhat alienated from one's surroundings. Finally, blocking the ears or the nostrils did not interfere much with functional usage for the nonfood products investigated in this study. However, it did decrease the experience of how good, how stimulating, and how intense the products were. Therefore, consumers' emotional product experiences nevertheless seem to suffer when audition or olfaction is blocked.

In combination with the existing literature, the two studies discussed above indicate that visual information is of primary importance in user—product interactions, because of its support to functional interactions, like executing tasks (Schifferstein, 2006). In general, vision provides the largest amount of information on a product within the shortest time frame. Furthermore, visual input seems to be linked most directly to stored knowledge, such as information regarding the method of production, region of origin, and product safety (e.g., Burns et al., 1995; Hinton and Henley, 1993). This large quantity of information most likely attracts the majority of a consumer's attentional resources, which leaves fewer resources available for the processing of any other sensory experiences. This may explain why people claim that they use their other senses more after vision has been blocked.

Certain characteristics that can be perceived through the sense of vision can also be perceived through the sense of touch (e.g., shape, location, and surface texture). As a consequence, the sense of touch also plays an important role in functional user—product interactions. However, vision and touch seem to have different preferences with respect to the type of sensory information they tend to adhere to. Material properties of objects tend to become more salient, compared to geometric properties or cognitive associations, when people base their judgments on touch rather than vision (Klatzky et al., 1987; Wastiels et al., 2013).

Product sounds provide feedback on what happens during the interaction. But sounds also provide information on the material an object is made of, its shape and its size, and its surface texture (Gaver, 1993; Hermes, 1998). In addition, a material's surface texture and shape influence the absorption or echoing of sounds in a space. Manipulating the characteristics of sound feedback can affect the perceived roughness of materials (e.g., Zampini et al., 2003).

The functions of taste and smell are linked to the perception of molecules. Smells give us clues as to whether an object is edible, stale, clean or dirty, has animal or plant origin, and so on. In general, olfactory cognition seems to be dominated by the affective dimension (Engen, 1982) and memories elicited by odors tend to be more emotional in character than memories elicited by other types of stimuli (Herz and Schooler, 2002).

This section has shown that each sensory modality plays a specific role in the experience of materials. Material properties gain or lose importance depending on the senses used for interaction. Using or blocking specific modalities influences the overall experience in terms of functional characteristics of the interaction, perceived product familiarity, or emotional experience. The sections below discuss how the different modalities work together or counteract each other in creating experiences.

HOW THE SENSES WORK TOGETHER IN CREATING EXPERIENCES

Consumer products can evoke feelings of intense enjoyment in multiple ways and through multiple sensory modalities. All the senses can contribute to pleasant experiences (Fenko et al., 2010a; Rozendaal and Schifferstein, 2010; Suzuki et al., 2006), but the question is how to design and orchestrate these pleasant experiences. How can one select materials in order to obtain pleasant combinations? Combining a number of pleasant sensory stimuli is by no means a guarantee for obtaining a pleasant product (e.g., Schifferstein et al., 2010). The extent to which individual stimuli fit together or are congruent is extremely important for the overall pleasantness judgment (e.g., Veryzer and Hutchinson, 1998). When selecting materials for products, it is therefore extremely important to evaluate the successfulness of combinations rather than evaluating the properties of individual materials.

The brain tries to integrate the information perceived through the different sensory channels into a coherent whole, in order to create a holistic product experience. But how does the brain accomplish that, if sensory channels are largely independent? Several mechanisms might be proposed that support the integration of sensory information (Schifferstein and Tanudjaja, 2004):

- Unified sensory perception
  People may perceive resemblances among sensory stimuli directly, because certain dimensions are shared across the different sensory modalities. For instance, perception shares the dimensions of intensity (weak–strong), duration, and spatial location (Boring, 1942). Consistent with this line of thought, von Hornbostel (1931) collected evidence that brightness was a universal sensory dimension.
- Environmental contingency between sensory messages
  Although object information is transmitted through a number of independent channels, some information may be perceived through multiple channels. For instance, the size of an object is conveyed not only through its visual appearance, but also through its haptic size and its weight, through the pitch of the sound it makes when you tap on it, and perhaps the intensity of its smell. As a consequence, people are aware of the contingencies between these different types of sensory signals. They are able to extract information derived from one sensory modality and use it in another. People can, for example, know a shape by touch and identify it correctly by sight (Calvert et al., 2004).
- Crossmodal correspondences
  People may perceive correspondences between stimulation in different sensory modalities. These correspondences may develop through perceptual learning. For example, people may have learned that the smell of caramel usually coincides with a brown color. Even when people experience difficulty in identifying the smell of a banana, this odor may elicit the association with fruit or, even more general, with food. Thereby, these associations limit the amount of colors that seem appropriate.

Enhancing the congruence of sensory messages in product design is desirable from an ergonomic perspective, where coherence helps to clarify what a product is about and what it can do. In addition, perceived unity in visual stimuli has been shown to correlate with ratings of both aesthetic appeal and liking (Veryzer and Hutchinson, 1998). Therefore, multisensory coherence is likely to be positively related to consumer preference.

In product design, explicit attention to all sensory modalities is typically found in toys for small children. In toy design, different shapes, patterns, and bright color contrasts are often combined with soft and hairy or smooth and slippery tactile feels, sound effects (bells, rattles, or musical melodies), and sweet smells. In products for grown-ups, we find explicit consideration of all the senses, for example, in the cushions made by Claudia Zhao, who combines different shapes with colors and prints, with soft and flexible fabrics, and the smell of lavender (Figure 2.1(a) and (b)). Another classic example is Alessi's "Mary Biscuit" designed by Stefano Giovannoni. This plastic biscuit box with rounded edges feels soft and warm to touch, makes only soft noises when you handle it, and the box seems to invite the user to cuddle it. In addition, the vanilla odor that is used to impregnate the cover may evoke nostalgic memories. In contrast to the typical metal biscuit boxes that feel cold and have sharp edges, the "Mary Biscuit" container enhances the coziness of social visits (Figure 2.2).

However, in some cases, designers may want to evoke surprise by introducing sensory discrepancies or uncertainties. Up to 6% of designs presented in the International Design Yearbooks (1999–2004) incorporate some form of visual-tactual incongruity (Ludden et al., 2008). In many cases, these incongruities involve a material that has tactual properties that are different (e.g., heavier, stickier, and more flexible) from a material with a similar appearance. The challenge in these cases is to combine familiarity and originality within the same design (Hekkert et al., 2003). Surprising products attract attention, offer new experiences to users and trigger further exploration of the product. However, in order for these products to be perceived as pleasant and amusing, it is important that the visual-tactual incongruities are judged to be appropriate (Ludden et al., 2012).

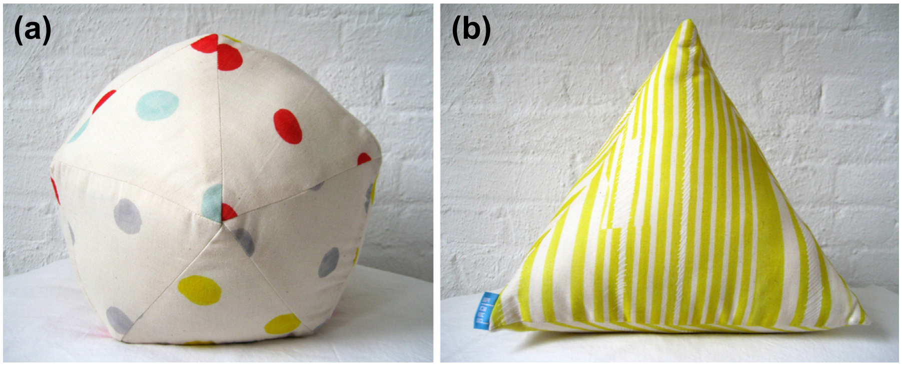

FIGURE 2.1(a) and (b)

Cushions designed by Claudia Zhao. *Image courtesy of Claudia Zhao.*

FIGURE 2.2
Mary Biscuit, biscuit box designed by Stefano Giovannoni. *Image courtesy of Alessi spa.*

SENSORY DOMINANCE IN MATERIAL PERCEPTION

Popular belief holds that vision tends to dominate human experience. When people are asked which sensory modality they would miss most if they lost it, the majority is likely to indicate vision (Fiore and Kimle, 1997). However, the sense of vision is unlikely to dominate in all types of everyday situations: people use their sensory abilities differently depending on whether they drive a car, bite into a banana, listen to the radio, or undergo a massage. Therefore, the relative importance of the sensory modalities is likely to depend, for instance, on the product with which the person interacts and on the type of task performed. In a study comparing the conscious evaluations of the relative importance of sensory modalities, Schifferstein (2006) found that people rated the importance of vision high for most products. However, there were a substantial number of products for which the sounds (washing machine, CD player, electric drill), tactile properties (computer mouse, pen, bath towel, sponge), smells (shower gel, deodorant), or taste characteristics (soft drink, cookies) were regarded more important than the visual aspects.

In multisensory perception, the sequence in which different stimulus aspects are perceived is important for the properties of the final percept. Generally speaking, after perceiving some properties people are likely to infer other, related properties for the same object. For instance, after seeing a big chair, people presumably expect the chair to be heavy as well, because they know that objects tend to get heavier as they increase in size. Because vision is often the first modality to perceive certain object properties, the expectancies generated on the basis of visual properties are likely to affect subsequent perception in other modalities. These inferred associations may lead to biases: in a series of objects with identical weights but different sizes, the weights of the bigger objects tend to be underestimated (e.g., Anderson, 1970).

Time also plays a role in sensory dominance relationships in product experience. Fenko et al. (2009a) observed that the sense of vision dominated the product acquisition process for many different types of products, probably because many products could not be interacted with actively during buying. However, during product usage, the importance of the other modalities increased and often surpassed the role of vision in a way that was dependent on the specific product.

INTEGRATING VISION AND TOUCH: THE EXPERIENCE OF WARMTH

Warmth is an important experiential characteristic for clothes, home interior, and some leisure-related products. In the general assessment of warmth, a combination of factors will influence the experience. The most literal aspect of warmth is related to the thermal perception of product characteristics. However, on closer inspection, warmth is a multisensory product experience that may include visual, olfactory, gustatory, and auditory components as well as other tactual aspects, such as roughness. Furthermore, the experience of warmth also contains a figurative aspect, associated with the metaphorical meaning of warmth. We will discuss each of these aspects below.

Tactile warmth

Objects made of different materials feel thermally different. For instance, wood generally feels warmer than metal, even though both materials are at room temperature. This effect is caused by differences in the thermal properties of the materials. An object that is below body temperature will extract warmth from the skin upon touching it, and the faster this heat extraction occurs, the colder the perception will be. High thermal conductivity allows heat extracted from the finger to spread quickly to other parts of the object, thus enabling the object to extract heat from the finger faster. Materials with low temperature resistance are thus considered "cold" (e.g., glass and metal) and those with high temperature resistance as "warm" (e.g., wood and plastic) at room temperature (Ashby and Johnson, 2002). This temperature resistance refers to the material's thermal conductivity k, which describes a material's ability to transport heat (Callister, 2007).

The temperature one actually perceives upon touching a surface is related to the contact temperature T_c (Lienhard and Lienhard, 2003). Besides the thermal conductivity and initial material temperature, this contact temperature also depends on the material's density ρ and heat capacity c. The contact temperature is closely related to a material's thermal effusivity $(k\rho c)^{1/2}$ (Ashby and Johnson, 2002; Obata et al., 2005).

In addition, the material geometry has an effect on the thermal perception: a thick bar will conduct heat away from the finger more easily than a thin foil (Bergman Tiest and Kappers, 2008). Furthermore, the surface geometry, like the roughness, may also influence the experience of warmth, as the contact surface between the material and the skin will be small for very rough surfaces compared to smooth surfaces.

Wastiels et al. (2012a) investigated the correlations between specific physical parameters of materials and the perception of warmth for different sensory modalities. For visual as well as tactile evaluations of warmth they found negative correlations with the logarithmic function of the thermal effusivity. Because the thermal behavior of a material cannot be perceived visually, these results suggest that the visual assessment of material warmth is influenced by the observers' tactile knowledge.

Color warmth

An object's color has a large influence on the experience of warmth. Most psychological research on color experience indicates that warm colors range between yellow and red-violet on the color circle (i.e., yellow, orange-yellow, red, and red-violet), and cold colors range between blue-violet and yellow-green on the chromatic circle (i.e., blue-violet, blue, blue-green, yellow-green). The perceived temperature of spaces painted blue-green versus orange-red tends to differ 3−4°C (Itten, 1970).

Wright (1962) showed a clear effect of hue on the perception of the warmth of colored squares, which was independent of brightness and color saturation. This author also found that the perceived warmth was higher for colors that were darker and more saturated. In a color meaning study that used five objects painted in six different colors (Osgood et al., 1957), consistent color effects were found for warmth, e.g., all objects appearing in red were consistently rated as warmer than those in other colors (see also Taft, 1997). Nonetheless, the warmth of a color also depends on the product context. For instance, Fenko et al. (2010b) found that perceived color warmth followed general color theory for a breakfast tray, but not for scarves. This implies that the validity of the predictions of general color theory should always be verified within the context of application.

Glossiness and roughness

Surface gloss may also influence the perception of warmth. Walls with glossy paint or glazed tiles are experienced as being hard, whereas a finely grained surface wall seems softer (Thiis-Evensen, 1987). Thiis-Evensen (1987) reasons that a fine texture is associated with porosity and, thereby, with a warm and protected space. In an experimental study of indoor wall materials, Wastiels et al. (2012b) showed that the local surface roughness had an effect on warmth perception, irrespective of the material's color, with rougher surfaces being perceived as warmer.

Comparing the contributions of vision and touch

All the different senses are used simultaneously and thus may influence the overall perception of warmth. However, it remains to be established empirically to what extent each sensory modality contributes to the overall experience. Experimental studies have shown that the contributions of the sensory modalities to experience aspects tend to be product dependent (Fenko et al., 2009b).

Fenko et al. (2010b) investigated the relative importance of color vision and tactile perception for the product experience of warmth. In a prestudy, participants rated the warmth of various colors and materials and, subsequently, the authors picked one warm and one cool stimulus for each sensory modality. For the main study, the authors created different types of products (scarves and breakfast tables) by combining these warm and cold stimuli (colors and materials) in all four possible combinations and asked respondents to evaluate the warmth of each product. The results demonstrated that for both these products color and material contributed equally to the judgments of warmth.

In a similar study investigating the contribution of material and color to the perceived warmth of wall elements, however, Wastiels et al. (2012a) found that vision clearly dominated the experience. Responses for a visual condition were similar to those in a multisensory (vision + touch) condition, whereas the results in the touch-only condition highly deviated. Apparently, when wall materials are perceived visually, touching the material does not alter the perception of material warmth. Additional studies on sample sets varying in color and roughness (Wastiels et al., 2012b) revealed that the effects of color on the perception of warmth were considerably larger than the effects of roughness. These outcomes support the idea that vision has a very large impact on the general assessment of material warmth within an architectural context.

Associations and metaphorical meaning

For understanding multisensory experiences, it is important to realize that they are not based solely on the information people perceive through their senses. The different meanings associated with the warmth concept are numerous. They relate to enthusiasm, liveliness, excitement, friendliness, sincerity, loving, passion, arousal (The American Heritage Dictionary of English Language, 2009), affection and tenderness, comfort and coziness, sexuality, or anger (Fenko et al., 2010b). Things that were once alive and warm, like the fur of a polar bear rug, or the leather of a chair, may carry an association with previous life (Heschong, 1979). In addition, materials that keep our bodies warm, like a woolen or fleece scarf, are associated with warmth (Fenko et al., 2010b). These cognitive associations affect the way in which people perceive, experience, and evaluate materials. Hence, for grasping the multisensory experience of the warmth of a material the product function and the evocation of associations should be taken into consideration, next to the impacts of the different sensory channels, as discussed in Chapter 1.

CONCLUSIONS

People see, hear, touch, smell and taste the world they are living in. Materials are the most basic elements in this sensory world. Materials are red, dark, heavy, rough, loud, glossy, smelly, wet, sturdy, echoing, and so on. Each material has a specific set of sensory attributes that interacts with the light, air, and people surrounding it. It tends to trigger a specific set of sensory impressions conveyed by the different sensory modalities. But the sensory material attributes are only part of the sensory story: there is no single description of how a material will be experienced. The multisensory perception is related not only to the material properties, but also to the context in which the material is used, the intentions of its user, and any cognitive associations that are evoked. Depending on the usage context, the material (or product) will be manipulated or interacted with differently. This will influence which senses are used, the way in which they are used, the degree to which they are in the center of attention, their relative importance during the interaction, and so on. Keeping these different and dynamic sensory impressions in mind while designing a product or space and choosing their materials can help designers in creating holistic, rich, and coherent experiences.

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CHAPTER 3

Tactile Aesthetics of Materials and Design

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CONTENTS

It is generally agreed that factors influencing material selection in today's design practice will go beyond the conventional domains, not only to enable better functionality, but also to build a unique product image and enhance the positive user experience. Among these factors, information about sensory interaction with materials, as the initial route of the user–product interaction, plays a significant role in the experience process.

A person's experience with a product is multifaceted. Desmet and Hekkert (2007) proposed a three-level product experience framework consisting of aesthetic experience, experience of meaning, and emotional experience. Donald Norman (2005) indicated three levels of product characteristics to be considered for design and connection with emotions: visceral level, behavioral level, and reflective level. The visceral level is all about appearance, to some extent, relating to the aesthetic experience. Most researchers agree that aesthetic experience refers to the pleasure or experience of delight gained through sensory channels (Hekkert, 2006; Ulrich, 2007), which is considered to be the immediate feelings evoked when experiencing the product via the sensory system. Sensory experience, differing from cognitive experience, is usually rapid, involuntary, and aggregate assessment, and is the core of aesthetic appreciation of product. As materials are the media through which the product is formulated, sensory experience with materials contributes significantly to the interpretation of experience with the whole product and it provides

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fundamental evidence for material selection. However, there is still a long way to go before mature theories regarding sensory experience or interaction with materials will have emerged.

In addressing sensory interaction with materials, equivalent terminology may need to be established for a convenient comparison with technical or functional properties of materials. A term "sensory properties" of materials has been used as a counterpart in previous research (Hiroyuki et al., 1985a; Zuo et al., 2004). It refers to those properties of materials that can be perceived by humans via sensory organs and can evoke physiological and psychological responses (Zuo et al., 2004), which include color, texture, sound, smell, and taste of materials. However, sensory interaction with materials is a system and process, where inputs from both objective properties of materials and subjective responses from people are integrated, together with the influence of environmental context. The terminology to be used depends on the focus of interest during this process. If biased on the material aspect, we recommend that the term "sensory properties" is used; if focused on the user aspect, the term "sensory feelings" may be more suitable. A more general term "sensory perception" of materials is used to reflect the whole process and the entire information of not only the sensory properties of materials but the users' feelings that are beyond the sensory domain, to also include the emotional domain and the semantic domain (or the domain of meaning).

There is evidence that most of the research work on sensory perception of materials is available in the case of visual perception, visual feelings, in terms of color and visual textures, etc. Other sensory modalities, particularly touch, have been less investigated. However, tactile interaction with materials has shown great potential and has been increasingly utilized in design practice. A recent survey, conducted at Tsinghua University across the design sectors of industrial products, architecture, and fashion, has shown that the tactile features of materials are the most expected materials information requested by design professionals, followed by ecological/environmental, visual, cultural, and economic information, as well as information about material providers. At sales points (physical shop), the decision of consumers to buy largely depends upon the dynamic user—product interaction beyond purely visual judgment of the quality, particularly the tactile feelings of materials, the potential, and all details felt during operation trials.

The main issues regarding tactile interaction with materials will include how people describe their feelings of materials including their emotional response via the sense of touch, how these subjective feelings are correlated and change under different conditions such as material category, how other sensations (e.g., vision) will impact on the tactile perception (either enhance or impede), what parameters of material physical properties dominate certain features of tactile feelings, and how the information can be integrated as a resource for design professionals to share. The following sections of the texts will discuss these issues from current available research work conducted by both the authors and other scholars.

TACTILE PERCEPTION OF MATERIALS

Taking tactile perception of materials as a system or process, it is related to both the objective properties of materials and the sensory features of touch. In this section, we will first look at the concept of material texture and then address the way people feel the material texture via the sense of touch.

Concept of texture

We understand that texture and texture combination can have a strong sensory impact and bring aesthetic appeal. Hundreds of thousands of textures can be generated from different resources such as insights from nature, innovation in materials and processes, virtual reality, fantasy of mind, and daily and social life, etc. (Zuo and Jones, 2005). However, not every one of us has speculated on the nature of texture. Understanding the essence of texture will give insights of the fundamental mechanism of "how texture can be formulated", so that we can appreciate, manipulate, or create texture effects more sophisticatedly.

Among the sensory properties, color, sound, smell, and taste are relatively easy to identify because they correspond clearly to a certain physical energy form (or physical stimulus), and are related to particular sensory organs. Sensation and perception of color is related to "light" and the organ of "eyes"; sensation and perception of sound is related to "sound waves" or "vibration" and the organ of "ears"; and sensations and perceptions of smell and taste are related to chemical molecules and the organs of "nose and tongue", respectively. Comparatively, texture is a more ambiguous property. There is not a definition that can be commonly accepted for texture. Both the physical energy form of texture and the organs of sensation-perception of texture are more complex. Texture can be perceived via vision, touch, or even influenced by sound, smell, and taste, which can be particularly reflected in feeling a texture of fruit or food. When we take a bite of an apple, the fragrant flavor, crispy sound, juicy and delicious taste, combined with the color and skin characters via vision and touch, create the whole robust impression of the apple's texture. When comparing the texture of a glass beer bottle with that of a plastic one, the sound difference (brittle and clashing for glass, dull for plastic) significantly contributes to different feelings of these two materials' textures. It is therefore more complicated to identify the nature of texture. Especially, texture perception by touch has a considerable number of issues to be clarified due to the many variables, such as body contact position, passive touch or active touch, skin character, touch speed, pressure and vibration, etc.

Generally speaking, textures are ubiquitous. A piece of silk cloth, a fluid of melted chocolate, a chapter of music, a painting, a poem, soil, water…all have a texture because they have the structure in which the constructive components (silk yarn, food ingredients, music notes and pitches, pigments, words…) are piled and organized in a certain way. This is the objective side of texture. On the other hand, it is through the senses and perception that people realize and appreciate textures, which can differ significantly from individual to individual. Thus, from a general perspective of cognition, texture is the sum of features of anything that essentially results from the structural arrangement of constructive elements. However, when we describe and communicate texture with each other via our senses and perception, texture becomes a "perceived texture". Setting this differentiation, in the case of a material or an object, we propose a definition for a material texture: the geometrical configuration and physical—chemical attributes of the surface (two dimensional) or the bulk (three dimensional (3D)) of materials/objects. On the other hand, the perceived texture of materials is defined as a synthesis of physiological and psychological response and impression to the geometrical configuration and physical—chemical attributes of the surface or the bulk of materials/objects. Under certain conditions (e.g., by vision), the response to geometrical characteristics may be dominant over physical—chemical attributes of texture, or the inverse, under other conditions (e.g., by blindfold touch). The "synthesis" means the response to geometrical characteristics and physical—chemical characteristics could interact with each other, and there will be more derived contents beyond these two aspects, as will be seen in the perception dimensions discussed in Section Dimensions and lexicons of tactile perception of materials.

Fundamentals of the sense of touch

Most fundamental research of touch has been conducted in the field of psychology, and the main focus of interest is to discover the perception mechanism, e.g., role of vibration in perception of roughness, with both the external factors (object) and internal factors (skin, finger moving rate, applied fingertip force, etc.) taken into consideration. The main target of this kind of research is to understand human ability and manipulation of touch behavior in daily life. The documented pioneer study on touch can be dated to approximately the 1920s, conducted by Katz (1925, 1930, 1989).

Understanding the fundamental phenomenon and features of the touch process will help in observing and analyzing tactile interaction with materials, and will be useful in guiding experimental research design and explaining some of the experimental results. Touch is usually classified as somatosensation, which generally refers to sensations of the body. In the initial stages of tactile perception, sensory processing begins in receptors. A given receptor cell will detect particular energies or chemicals. Typical receptors that are found in both hairy skin and glabrous skin (hairless skin) include free nerve endings, pacinian corpuscles, Merkel disks, and Ruffini endings (Pinel, 2000). These receptors have different functions and adapt to stimuli at different speeds. For example, under a constant pressure applied to the skin, the stimulus (pressure) evokes an activation of all receptors, but after a few hundred milliseconds, only the slow-adapting receptors remain active. This can explain why people are often unaware of some constant tactual stimuli. For instance, we are usually unaware of the feeling of our clothes against our body, or the glasses standing on our nose, unless we focus attention on them or move them consciously. Therefore, in order to identify objects by touch, dynamic manipulation is required so that the pattern of stimulation continually changes (Pinel, 2000). In other words, motion touch or dynamic touch is more effective than static touch in identifying object properties including textures. This is also the reason why in most of the experimental research for materials tactile experience, motive touch was adopted in the tests.

Touch can be divided into three main types: passive touch, active touch (Gibson, 1966), and intra-active touch (Bolanowski et al., 1999). Passive touch refers to a touch under the condition in which the subject is stationary and the stimulus is imposed upon the skin. Active touch refers to a touch under the condition in which the stimulus is stationary and the subject actively explores an object or surface. Intra-active touch, as an active/passive activity, means actively moving an object over another surface of the body which is stationary. Our interest is focused more on active touch, because in most cases, especially at the first contact with the product at the sales point, active touch may be more involved in the decision to purchase. Although early scholars used “tactile” for “passive touch” and “tactual” or “haptic” for active touch (William and Emerson, 1982), we tend to equalize these two terms.

Dimensions and lexicons of tactile perception of materials

Scholars have endeavored to extract dimensions to explain a person’s tactual feeling of a material. To list a few, Hiroyuki in his early research used four dimensions for aluminum, iron, glass, and plastic: (1) thermal character (*warm—cold*), (2) moist character (*wet—dry*), (3) surface contour (*rough—smooth*), (4) denseness (loosely packed—densely packed), with preference (*like—dislike*) as a general impression (Hiroyuki et al., 1985a). However, in a later study (Hiroyuki et al., 1985b), he used 25 dimensions via primary factor analysis for visual and tactual evaluation of leather texture, such as *isotropic, anisotropic; warm, cold; with wet absorption, without wet absorption; with wet transmission, without wet transmission; smooth, rough; dense, loose*; etc. Hollins et al., after tactile evaluation experiments on 17 samples of various materials, drew a 3D tactile texture perception space: roughness (*rough—smooth*), hardness (*hard—soft*), and springiness (Hollins et al., 1993). Chen used *warm—cold*, *slippery—sticky*, *smooth—rough*, *hard—soft*, *bumpy—flat*, and *wet—dry* to examine tactual perception of cardboards, flexible materials, and laminate boards and their relationship with surface physical properties, for confectionery packaging application (Chen et al., 2009). Despite showing some commonality, the above-mentioned words or word pairs of tactual perception of materials from different research differ in the following aspects: (1) different material categories, (2) different application contexts (if there are any), and (3) different foci of interest (purely sensory, emotional, semantic, etc.). A simple understanding is that a few limited words or word pairs may not reflect a complete description of tactile perception. Strictly speaking, these words or word pairs may be suitably regarded as "descriptors" (which we call texture "lexicons") rather than "dimensions", as we propose "dimensions" to be a general framework that can be applicable for any case of tactual perception of any kind of material. From experimental research, we have summarized a four-dimensional framework to describe a person's tactual perception of materials/textures on a general and macro level. On the second level, there will be a number of lexicons that represent typical tactual description within each of these dimensions (Zuo et al., 2001).

1. *Geometrical dimension*: this dimension describes the subjective response to the geometrical configuration of a material surface. High-frequency lexicons used in this dimension include *smooth—rough*, *fine—coarse*, *plain—bumpy*, *regular—irregular*, *linear—nonlinear*, etc. The most widely applicable lexicon is *smooth—rough*, while *fine—coarse* is a size-related description; the other lexicons are descriptions of more macro features over a larger area of the surface.
2. *Physical—chemical dimension*: this dimension describes the subjective response to the physical and/or chemical attributes of a material surface, which is based on the interaction between skin and surface via energy exchange (e.g., heat), matter exchange (e.g., absorption of sweat), or deformation (e.g., in perceiving softness). High-frequency lexicons used in this dimension include *warm—cold*, *hard—soft*, *moist—dry*, *shiny—nonshiny*, *sticky—nonsticky*, *heavy—light*, etc.
3. *Emotional dimension*: this dimension describes the affective and hedonic feelings that are evoked by touching the material surface. High-frequency lexicons in this dimension include *comfortable—uncomfortable*, *lively/cheerful—dull*, *elegant—ugly*, *modern—traditional*, etc.
4. *Associative dimension*: this dimension describes anything that is associated with the subjects' imagination when the material is being touched, based on the analogous attributes of the material surface with the users' past experience. It is much more individual dependent. Lexicons in this dimension are random and may have low frequency of replication, for example, *plasticlike* (the material in fact may not be plastic), *mattlike*, *rubberlike*, *tree bark-like*, *animal skin-like*, *honeycomb-like*, *dimplelike*, *icelike*, etc.

The first two dimensions are more biased on the material aspect, and thus will show higher commonalities among individual perceivers, while the latter two are more biased on the user aspect,

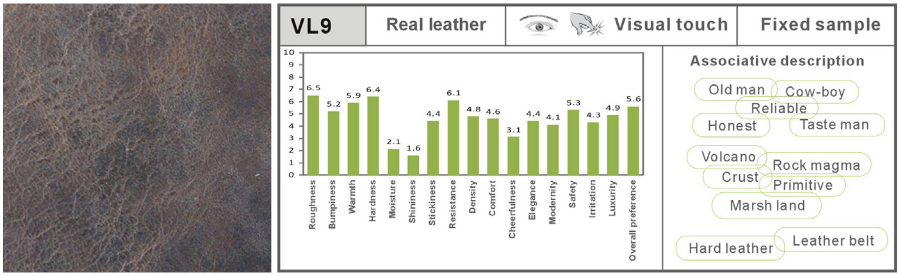

FIGURE 3.1

Typical description of a leather texture within the four dimensions.

and thus will show considerable deviation among individuals. A typical description of a leather texture is shown in Figure 3.1, generated from research by the authors. The ranked evaluation in the chart is an average score from a number of tests within the geometrical, physical—chemical, and emotional dimensions, while the associative description in the right column is a result gathered from the responses of the test participants.

The most sensitive lexicons to be used depend on conditions such as material categories, sensory modalities (e.g., whether vision or another sense is integrated), subject groups, etc. In addition to looking at each individual sensory feeling represented by a certain lexicon within a particular dimension, finding the interrelationships among the responses within the four dimensions is more important. For example, experiments show that a perceived *smooth* surface (geometrical dimension) corresponds to a feeling of *moist*, *sticky*, *shiny*, and *cold* (physical—chemical dimension), while a rough surface corresponds to a feeling of *dry*, *nonsticky*, *nonshiny*, and warm. A perceived *smooth* surface (geometrical dimension) can be felt *oily* (associative dimension). A lively/cheerful response (emotional dimension) mainly corresponds to a perceived *shiny* surface (physical—chemical dimension) (Zuo, 2003).

The correlations among the four dimensions have been found not only in the case of isolated material samples, but also in the case of product contexts. For example, a case study of hair dryers conducted by the authors indicated that a "*shiny*" surface corresponds to "*cheerful/lively*" feelings, a "*black shiny*" plastic surface evokes the associative feeling of "*high class*" or "*high-quality black cars*", or a "*metallic*" "*gray*" or "*smooth*" plastic surface is associated with "*hi-fi*" or a "*space gun*" (Zuo, 2005). However, different contexts may strengthen, weaken, or completely alter the extent or direction of correlations.

Such correlations among the four dimensions on a microscale reflect the relationship between aesthetic experience (corresponding to dimensions 1 and 2), emotional experience (dimension 3) and the experience of meaning (dimension 4). In fact, material experience contributes significantly to the experience of the whole product, and can be regarded as a subdomain of product experience (Zuo, 2010). Similar correlation between sensory/aesthetic experience and emotional experience or experience of meaning can also be found in other scholars' research. For example, Karana found that transparency and smoothness of materials were very much associated with the meaning of "sexy", while hardness and dark colors of materials correspond to expressing professionalism within 125 selected consumer products (Karana et al., 2009). Another interesting example is the correlation with perceived weight. Despite some forms of weight illusions from a material's visual elements such as size, color, etc., actual weight is still decided by tactual judgment of the material density. Although perception of weight comes from kinesthetic senses, whether a material feels heavy or light still correlates to tactual feeling, and the perceived heaviness or density, by our research, is attributed to the physical–chemical dimension. A workshop co-organized by Materials KTN and Royal College of Art in the United Kingdom has reviewed the perception of weight in products and confirmed some concepts, for example, products presented in containers or packages made of heavier materials are perceived as being of higher quality (Hollington, 2011). It is the correlations between the four dimensions of material texture perception, or more widely speaking, the relationships between the sensory/aesthetic experience of materials and the emotional experience, the experience of meaning that can provide reference and insights for material/texture selection.

UNDERLYING MATERIAL PARAMETERS

From the perspective of material science, conventional mechanical or physical/chemical properties of materials (engineering properties) are derived from the features of their microstructures, either at the atomic/molecular level or at the microscopic level (a group of atoms). For example, a piece of aluminum oxide made of a single crystal will display transparency, while when it consists of numerous tiny crystals connected together, it is translucent (due to light scattered at the crystal boundaries), and when the multicrystal structure also contains a large amount of pores or void spaces, the aluminum oxide becomes opaque (Callister, 2010, p. 4).

Sensory properties are intersected with engineering properties of materials. For instance, the above-mentioned transparency is both an optical property and a sensory one. But a sensory property is not equal to an engineering property as it is judged by our sensory organs. For example, "softness" is not an engineering property but a sensory one. A soft material deforms or deflects under external load (e.g., pressure from your fingers), and when the load is released, the material returns to its original form. The underlying parameter dominating this elastic behavior of this soft material is actually the modulus (Ashby and Johnson, 2002; p. 68), which is a material property based on structure regardless of its shape or size. So, from an objective perspective, sensory properties are still related to the structure of materials, and can possibly be manipulated by a certain key parameter.

However, some sensory properties might be dominated by the surface structure rather than the bulk structure of a material. For example, the subjective feeling of roughness or smoothness mainly depends upon the material's surface structure. Thus, the same material (with the same 3D bulk structure) can display a differing extent of smoothness/roughness via different surface treatment processes. Other sensory properties may be dominated by the 3D structure of the whole bulk of the material, such as perceived softness, or by both surface structure and bulk structure of the material, for instance, perceived warmth has shown correlation with both the material conductivity (bulk structure) and surface roughness (surface structure). Finding the dominating or relevant physical property(-ties) or parameter(s) of materials that influence the sensory feelings of people to the material is significantly important so that the experiential domain of materials and the technical domain of materials can be bridged.

It should be pointed out that the actual correlation between perceived texture and the related physical properties might be rather complex. This is reflected by the phenomenon that one physical property may correlate with more than one aspect of subjective response. For example, the physical roughness correlates not only to the subjective roughness, but also to the subjective warmth. On the other hand, one aspect of subjective response might be influenced by more than one physical property. For example, the subjective warmth can be influenced by the material thermal conductivity or surface contact temperature (Hiroyuki et al., 1985a), and also by the physical roughness of the surface under tactual condition, and even by the surface color under visual condition. In other words, unlike the traditional "one-to-one" psychophysical relationship, the relationship between a subjective perceived texture and material physical properties tends to be a "one-to-more" or "more-to-one" relationship (Zuo, 2010). This conclusion can also be found in other scholars' research work. For example, Chen has indicated that perceived moisture (wet–dry) correlates to the physical properties of roughness, compliance, friction coefficient, and rate of cooling, while friction coefficient of a material can correlate to perceived warmth, roughness, bumpiness, and moisture (Chen et al., 2009).

In preliminary tests, we have found that the most obvious parameter of physical roughness that influences our tactual judgment of roughness tends to be the arithmetic mean roughness (Ra) (Zuo, 2003). However, due to this "one-to-more" or "more-to-one" relationship, at the current stage it is still difficult to decide which physical property or which parameter will dominate every corresponding aspect of perceived texture (represented by the texture lexicons), until a large amount of experimental work is completed.

OPTIMUM TEXTURE DESIGN

It is challengeable and may be too ambitious to put forward the concept of optimum texture design. The main challenges come from

1. Complexity of goals. The connotation of "optimum" depends upon the goals that the selected texture aims to achieve, but goals can be multifaceted, varying from purely sensorial pleasure, to particular emotional feelings, and to fulfilling pragmatic compatibility.
2. Complexity of contexts. Context of application varies case to case, and it is difficult to find an optimum texture that is generally applicable. For example, a good texture for a car steering wheel might not be suitable for a knife handle.
3. Complexity of senses. In a real application, the end effect of material/texture selection does not come from tactual feeling only. As indicated in the early research work of Taylor, Lederman, and Gibson, "usual perceptual experience comes from rich and complex patterns of stimulation of various senses, from coordinated variation in the outputs of logically independent sensory receptors, from information deliberately sought and from information fortuitously acquired, from patterns of motion kinesthetically sensed combined with patterns of motion visually, auditorily, and tactually sensed" (Taylor et al., 1973).
4. Complexity of users. Different users or user groups will differ in the sensory feelings within the four dimensions specified previously, particularly in the emotional and associative dimensions.

However, having these challenges in mind, it is still necessary and possible to find the most appropriate texture to satisfy particular application requirements by setting up a series of categorized scenarios. For example, for hand-touch products, scenarios can be categorized into static touch, dynamic touch, touch with vibration, etc. These scenarios can be a part of a live project in collaboration with industry or simulation in a research laboratory. Such results can be used as reference for selection of textures to achieve similar goals under similar product contexts. This is realized by looking at the perception results in both cases—physical material samples and physical product samples, followed by comparison and analysis. The correlations among the sensory responses within the four dimensions of texture perception play a significant role. Basically, any isolated sensory response within the geometrical dimension or the physical–chemical dimension can be regarded as "neutral". For example, it is hard to say whether *smooth* or *rough* is either a good or bad attribute. To decide which particular texture attribute (e.g., *smooth* or *rough*) is optimal for a particular application, or is chosen by users as the most preferred one, will depend upon several aspects. Apart from pragmatic or functional appropriateness (e.g., an effective *grip*, *push* operation with the product), the connection to emotional feelings and association to a particular meaning are important criteria.

For example, in order to explore an ideal tactual texture for a handle of a hand grip product in the case of static touch, we conducted experiments using shape-simulated material samples and real products. Figure 3.2(a) shows the bar-shaped thermoplastic elastomer (TPE) and a set of hair dryers with handles in different textures as examples. By drawing the commonality of the correlations among the responses within the four dimensions of texture perception of all the experiments, we have found for a *comfortable* feeling, a "*smooth* and *nonsticky*" surface is expected. Usually, a mirror-polished *smooth* surface is

FIGURE 3.2
Experimental research in scenario of static touch for hand grip product: (a) bar samples of thermoplastic elastomer and (b) real product samples of hair dryer.

perceived as *sticky* probably due to the sweat absorbed to the surface, making the manipulation uncontrollable either "too *resistant*" or "too *slippery*". The essential feature of a "*smooth* but *nonsticky*" surface is to provide a "controllable grip" without an "accidental slip". For metals, surfaces with a satin finish, sandblasted (processed with fine-grained sands), and anodized match this better than other finishes. For polymeric materials, TPE or plastic with rubbery coatings (same as the middle handle in Figure 3.2(b)) match satisfactorily. However, the correlations usually are quite complex, and "trade-offs" often take place. When singular texture cannot achieve the goals of expectation, a suitable combination of different textures of one or more materials can achieve the optimal effects. For example, from our experiment, a "*smooth* and *shiny*" plastic (for a *lively*/*cheerful* feeling) coupled with a "*smooth*, *nonsticky*, *soft*, *warm*, but *nonshiny*" TPE would be optimal for a hair dryer handle.

Other scholars have also endeavored to explore the method of optimum texture design from different perspectives. For example, Sun, using Kansei Engineering and statistical analysis in terms of plastic samples, established a two-factor texture image space, sensory factor and utility factor, which were influenced by transparency and additives, respectively, and integrated this information into 3D software as a digital texture design tool (Sun et al., 2009).

In relation to the authors' own work, the theoretical framework and practical experimentation presented in this chapter has been used as the foundation for an online "material-aesthetics database". This is proving to be an effective tool in assisting the selection of materials/textures in product design projects, in conjunction with other material resources. The database (http://www.material-aesthetics.com) is under continuous development and is mentioned in further detail later in the book, within Pedgley's chapter covering new material selection tools.

CONCLUSIONS

Tactual interaction with materials is a dynamic process that needs input from both objective material properties and subjective responses, which is reflected in the four dimensions (geometrical, physical—chemical, emotional, and associative) that summarize the subjective tactual perception of materials. The correlations among the various feelings (represented by the lexicons within each dimension) play a significant role in materials selection, particularly for ideal texture design. These correlations often tend to be complex and therefore a trade-off usually has to be considered. An example has been shown for a "smooth but nonsticky" surface for a hand grip product in the case of static touch. Relationship between a sensory property of material and the underlying influential material parameters has a "one-to-more" or "more-to-one" feature. Finding the dominant parameter would be useful to pinpoint a good match to positive subjective feelings of materials through technical processes, but needs further experimental work.

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CHAPTER 4

The Sound and Taste of Materials

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CONTENTS

The question of what a material *is*, and how it is defined, lies at the heart of all materials disciplines. In broad terms, these questions encompass the processes of materials research, identification, selection and utilization, and thus impact on our studying, gathering, organizing and interactions with all *stuff*. However, much of the literature that discusses specific aspects of materials, from both scientific and artistic stances, does not directly address the question of exactly what a material is, and how it is defined.

Dictionary and encyclopedia definitions focus their attention on the role of materials as the stuff that comprises things, for example, "the matter from which a thing is or can be made" (OED, 1999). In the arts, what often occurs is a form of definition by default, where the word "material(s)" is used descriptively to denote the components of a work, product, or building. In these cases, the material is being referred to, understood, and in turn defined as the matter or substance used to create objects or products. A material becomes the input in the process of physical construction that influences the properties of that which is constructed as a result of the material's embedded materiality. This materiality is associated with classifications ranging from a qualitative aesthetic, sensorial, and behavioral appreciation of a material, to the specific cultural resonance of a material and its ability to connote *meaning*.

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Materials science and engineering are disciplines that revolve around the development, testing, and utilization of materials. The process of materials selection brings into focus the nature of this relationship, as the structure, properties, and behaviors of materials are researched and quantified in order to predict how a material will perform in a given scenario. The establishment of well-defined terminology ensures that information about a material is communicated in an exact manner: to talk of strength versus stiffness, for example, is not a semantic exercise but a precise quantitative description of mechanical behavior, as strength is defined as a resistance to crack propagation, while stiffness is the resistance to shape deformation (Callister, 2005). These concepts of strength and stiffness are also divorced from the scale of material sample, so the stiffness of a paper clip is defined to the same degree as the stiffness of a girder if they are made from exactly the same material, and is referred to as an intrinsic material property (although there is now a growing appreciation that there are size effects at the nanoscale).

The experimental tests that provide the terminology of materials and their mechanical behaviors are carried out for two main reasons: to simulate the conditions in which a material will be used and therefore "predict its service performance", and to gather "engineering design data" to check that the material meets its specifications (Martin, 2002). Information on the properties of materials, which is generated in these processes, is collected in databases. One such database is the Cambridge Engineering Selector, which offers the user the opportunity for the "rational selection of engineering materials and processes" through computational methods (GrantaDesign, 2012), a system developed within Cambridge University by Michael Ashby and his colleagues.

Processes of materials selection, appreciation, and interaction are very different for structures whose performance is not based solely on the physical scientific parameters, but also on sensual, tactile, aesthetic, and cultural factors. Creations such as buildings, interiors, clothes, pens, computers, vacuum cleaners, and mugs are structures in which human comfort, inspiration, and sensual satisfaction (for example) are important. Notions of how a material might function are not simply to do with scientific values of performance but notions of meaning and more qualitative attributes. Such structures we tend to call objects, and these are often designed by members of the arts community whose relationship with materials selection is very different to that of the engineer. It is in fact very diverse, with each type of practitioner having different methodologies and traditions.

There comes a point, however, when the type of question being asked of a material by an artist or designer requires an answer that involves something of the science of materials. The design of a successful product, for example, relies upon more than materials desire and approximation. Design training does not generally provide an in-depth scientific knowledge of materials, but more and more designers are taking it upon themselves to gain a greater understanding of the broader materials picture. Wishing to discover "how plastic is made" or "which metals are good for you to eat with and which are not" leads many product designers to ask "many materials science questions, and set out to answer them in the only way we know how: Google" (Berger and Hawthorne, 2008). The materials science and engineering model of materials selection, with formal terminology and mathematics, is often difficult to access and assimilate into projects by many designers and those coming to materials from an arts background (Ashby and Johnson, 2002). With this in mind, Michael Ashby and Kara Johnson wrote *Materials and Design: the Art and Science of Materials Selection in Product Design* (2002) in an attempt to bridge the gap between the approach of designers and engineers in relation to materials. Throughout their book, Ashby and Johnson bring quantitative analysis and qualitative attributes together for the designer to make informed materials selection decisions. They generate accessible graphical information that plots technical attributes and offers the opportunity of visual comprehension of scientific data sets. For example, a multidimensional scaling (MDS) plot of acoustic properties (acoustic pitch versus acoustic brightness) for a wide variety of material families is provided on p. 72 of Ashby and Johnson (2002).

Despite the diverse approaches used by arts practitioners—from potters to painters, product designers to jewelers—a qualitative, tactile, and hands-on approach to materials is often favored as a way of getting to grips with what a material is like (Esslinger, 2006). Specific materials expertise, encapsulated through experience and highly technical knowledge, is often key to arts practices. However, such methods are rarely generalized or accompanied by use of the structure–property paradigm of materials science. While quantitative analysis, testing, and microscopy are on the increase within the arts as engagement with scientific technologies increases (Ede, 2005 and Hauser, 2008), the practitioner's relationship with materials is still largely driven by use, manipulation, and appreciation of them on the macro level, from encounters with haptic and aesthetic analysis at the human scale.

This presents a problem, for, although there is a large amount of technical information about materials available for scientists, engineers, technologists, and industrialists to use in the making of objects, these quantitative data reveal little of their aesthetic properties, and these are the properties that are of predominant interest to the materials–arts communities. Indeed, there has been little work looking at how the physical properties of materials relate to their sensual and aesthetic properties. Within the world of materials, there can exist a split between the materials science community, those scientists, technologists, and industrialists who are interested in the physicality of materials, and those in the materials–arts community who are interested in the sensoaesthetic properties of materials. The two sides often do not speak a common language. The question is then this: how do we create a methodology that brings them together in a coherent, collaborative, and productive fashion?

SENSOAESTHETICS

Our work in developing a sensoaesthetic theory of materials attempts to shed light upon the aesthetic and perceptual side of materials through psychophysical and materials science methodologies. Although it may initially appear that a hard scientific discipline might not marry up well to the softer side of materials, upon closer inspection it is revealed that the way we interact with, and the emotion we feel from, all materials is rooted in their fundamental physical properties. We can consider the sense of touch as an example. The major factors that we use in the identification of materials by touch are warmth, softness, and roughness. If you feel something that is hard and cold to the touch, then you know it is going to be something like metal, glass, or stone. If you feel the surface texture, then you are more than likely to be able to identify exactly what material it is. All your senses are used to pick up on the physical properties of a material, and it is those physical properties that materials scientists define and measure. For example, metals generally feel cool to the touch because they conduct heat away from your skin very quickly. So we can say that, in general, materials with high thermal conductivity will be perceived as feeling cool to the touch. Or if an object is soft to the touch, then we can look at physical variables such as elastic modulus or plasticity to characterize the interaction.

The overall aim of our research is to attempt to fill in this gap by using scientific methods to study those properties of materials that are largely ignored by materials scientists, yet are vitally important to material art and design communities and coming under an increasing amount of scrutiny by those interested in the sensorial aspects of materials (Karana et al., 2009; Rognoli, 2010). The sensoaesthetic properties are strongly dependent on perception, and the study of perception falls within the realm of psychology. This work therefore combines psychophysics, the science of the senses, with materials science, a discipline driven by physical characterization. The result is a body of work that is moving toward the development of a sensoaesthetic theory of materials (Howes and Laughlin, 2011, 2012; Laughlin, 2010; Miodownik, 2007).

A material–object methodology

The experiments undertaken at The Materials Library (Laughlin, 2010) were designed to study the links between the aesthetic perception of materiality and the measurable physical properties of the materials themselves. A core concept of this research was to study these sides of materiality by staging *encounters* with sets of material–objects (Laughlin, 2010), rather than simply with materials. The deployment of the term "encounter" is used to describe the framed coming together of materials and people and aims to underline the role of the unexpected in such a meeting, and the possibility of a confronting experience. Confrontation should be considered here in terms of an arrestment of the senses, a moment that makes one notice, realize, or consider something outside of the usual, a moment or scenario where an unexpected occurrence, discovery, or experience punctuates our existence and results in a conscious noticing of matter. To facilitate this, we introduced the idea of the swatch. This is something familiar to us when choosing materials for certain applications, for example, swatches of textiles used by tailors and paints by home décor retailers. We moved beyond this material swatches to material–object swatches, an isometric set where form was kept constant and materiality was changed. This allowed for the study of perception of materials as a direct function of their physical properties.

THE SOUND OF MATERIALS

Sounds and music can have striking emotional effects on us, from joy and elation to the depths of despair. Sounds and their cultural resonances are in fact built upon the materiality of the objects used to create them. In the same way that the feeling of a surface through touch is rooted in our perception of the physical properties of that surface, the aesthetic and emotional connotations of sound can be linked to well-defined physical parameters. In this work, we set out to explore how changes in materiality affect changes in perception of sound using a set of custom-made objects. The two primary methods used to analyze the objects were participatory observation and acoustic testing.

The objects

To test the comparative acoustic properties of different materials and how these were experienced through perception, a swatch of tuning forks was made (Figure 4.1). In this way, the form was kept constant but

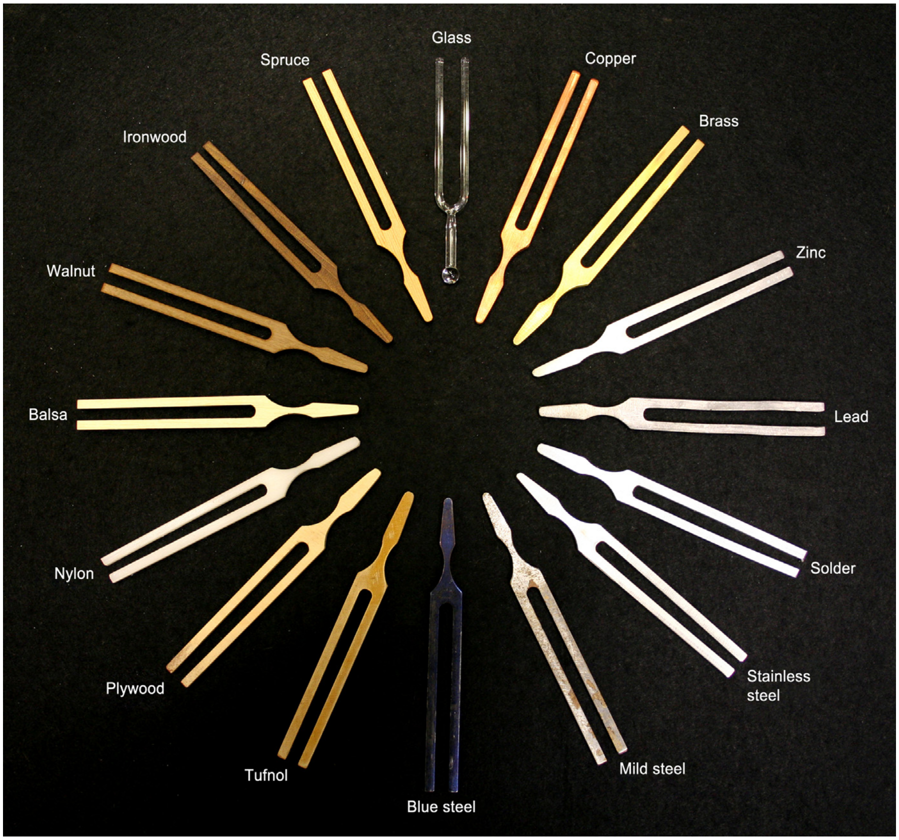

FIGURE 4.1
Sixteen tuning forks of varying materials made to render the micro performance of a materials structure as a macro experience.
Laughlin, 2010.

the material was changed. Given their status as an object with a specific use, their position on the material–object continuum is elevated above the metals from which they are composed. Changes in material enabled the resultant differences in the performance of the forks to be judged in relation two well-defined physical parameters: density and elastic modulus. Any shift in the frequency of sound produced by each fork would be a direct result of the materiality, rather than the form of the material.

The principle factors that influence the production of sound by a tuning fork are the shape of the fork (form), and then the density (materiality) and elastic modulus (materiality) of the material. The pitch of the note that a tuning fork produces is expressed as

$$f \infty \frac{1}{l^2}\sqrt{\frac{AE}{\rho}}$$

where f is the frequency of the fork, A is the cross-sectional area of the tuning fork (form), l is the length of the forks prongs (form), E is the elastic modulus of the material (materiality), and ρ is the density of the material (materiality). The creation of a set of tuning forks that keeps form constant and employs materiality as the variable enables the exploration of the density and elastic modulus, values that are not varied in commercially available tuning forks.

The quantitative evaluation of form is accessible and comprehensible at the human macro level of scale, whereas the materiality values are derived from a structural scale invisible to the eye. For instance, in the case of metals, the density is typically determined by the atomic mass, which determines the weight, and the crystal structure, which determines how closely the atoms pack together. The elastic modulus (stiffness) of metals is determined by the electronic structure of the atoms and the type of bonding present. Overall, the tuning forks were used to explore these invisible structures and properties in a way that rendered their effect as a macro, experiential phenomena that users could encounter through physically playing the tuning forks.

The results

The concept of the encounter was primarily defined by the haptic exploration of the material—object by the participants. For the tuning forks, this haptic exploration takes the form of the handling and physical playing of a tuning fork by a participant and the experiencing of the phenomena that occur. The qualities of the sound produced by a tuning fork are experienced as a note of a specific pitch (frequency), with a particular brightness (a combinatory factor of duration and amplitude). We used the tuning forks to investigate the effects of materiality on sound, with the exact frequency produced by each fork measured and the shift in pitch attributed to the change in materials.

The commercially made blue steel tuning fork, when struck, rang with a bright and sustained note. In contrast, the fork made of copper emitted a tone of low pitch and volume, and of a short duration, while brass emitted a tone of intermediate pitch but very long duration. An extreme example was that of zinc, which made no audible sound and the prongs deformed if struck forcibly. The wooden forks did not "ring" like the metals forks, but produced a single note of very little duration when pinched instead of struck. The range of notes produced is not insignificant, with obeche, walnut, and bass woods all producing tones higher than spruce, closer to the blued steel, while plywood, balsa, and iron wood all produce notes lower than spruce with both balsa and plywood emitting tones lower in pitch than the copper fork. The polymer forks (nylon and acrylic) produced no audible sound upon striking, but when pinched produced a low note with a dull thudding quality. With regard to the encountering of the tuning forks, all three aspects of performative agency were embraced, that of the doing participant, the functioning form, and the behaving material. These three elements of the encounter affect and depend upon one another, working toward the enactment of the material—object as a representation of acoustic phenomena that can be physically experienced.

The tuning forks were played and assessed by a group of musicians whose perceptions of pitch and brightness were judged against those of Ashby's and Johnson's MDS map for acoustic properties, mentioned earlier in the chapter. In terms of the frequencies produced by the tuning forks, we found broad agreement with the theoretical predictions, apart from a few anomalies. We also found that judgments of pitch made by musicians were also in agreement with the frequency measurements. The greatest surprise was that the pitch of disparate materials could be very similar, while the brightness of the note varies dramatically, due to variations in the material's coefficient of loss. Changes in material enabled the resultant differences in the performance of the forks to be judged in relation to density and elastic modulus. Any shift in the frequency of sound produced by each fork was a direct result of the material from which it was made and as a result, the isomorphic set of tuning forks went some way to practically demonstrating and conceptually representing the science of their materials.

Within the act of encounter, the set of tuning forks becomes a physical manifestation of both the frequency equation and the MDS map of acoustic properties mentioned earlier in the chapter. The tuning forks, the frequency equation, and the MDS map are in fact three versions of the same thing, three ways of representing the relationship between materials and acoustic properties. The effects of density and elastic modulus are not explained by the tuning forks themselves: this is part of the role of the librarian in discussing the encounter with the visitor. The effects of density and elastic modulus are experienced in the act of playing the tuning forks. As a result of the existence of the set of tuning forks, density and elastic modulus are "performed" by the tuning forks and enabled as a physical experience of acoustic properties.

THE TASTE OF MATERIALS

Similar to the way we related the aesthetic qualities of tuning forks to their underlying physical characteristics, we conducted an experiment to correlate taste characteristics of solid materials with their physical properties. The specific focus was on the differences in how "metallic" tasting a set of metal objects were in relation to well-defined physical variables.

Tastes are received through taste buds on the tongue. There are five generally accepted basic tastes: bitter, salty, sour, sweet, and umami (Ikeda, 2002). The perception of flavor and more general oral sensations are dependent on further factors such as smell, texture, and temperature (Lindemann, 2001). The concept of taste is generally associated with substances that we place in the mouth in order to consume. However, the experience of taste in relation to inedible matter is much less appreciated and understood. Although "metallic" is not commonly considered a basic taste, there is growing evidence that metal ions act as chemosensory stimuli in the mouth (Lawless et al., 2006). Lawless et al. (2006) showed that ferrous sulfate produces a distinctly different sensation from the traditional basic taste descriptors, all of which are thought to have unique receptors (Chandrashekar et al., 2006).

The chemical aspects of the taste of inedible materials are commonly discussed in terms of their standard electrode potential, which defines the susceptibility of a particular material to being oxidized (Bartoshuk, 1978). These potentials have been measured for most metals, and are believed to confirm broad trends of taste: metals that are highly susceptible to oxidization such as copper and aluminum have a noticeably metallic taste, whereas gold and silver are almost tasteless (Lawless et al., 2006). However, previous to our work there had been no systematic investigation into the relation between the physical or chemical properties of solid materials and their taste.

The objects

As an object, the spoon is at the heart of life, feeding us from infancy and accompanying us in both the preparation, sharing, and eating of food the world over, making it a culturally significant artifact experienced by a truly vast number of people (Petroski, 1992). We chose the spoon as an isomorphic form because of its high object status, being extremely recognizable and readily associated with eating and tasting, thus providing a material form that people would be conceptually and physically comfortable with having in their mouths. Teaspoons were identified as the ideal type of spoon for this study as the bowl of the spoon would be small enough to fit into any adult mouth with ease.

In making the spoons, a number of practical factors had to be taken into consideration. The sensitivity of mechanoreceptors in the mouth means that the tongue would instantly feel any differences in size and texture, no matter how slight. If the eye, hand, or mouth were to detect such differences, the isomorphic nature of the spoons set would be placed in jeopardy. It was therefore important to use a technique to make spoons that were both repeatable and exact. It was decided that preexisting teaspoons made from stainless steel would be coated in a number of different metals, and the final swatch is shown in Figure 4.2. Six stainless steel teaspoons were electroplated with copper, gold, silver, tin, zinc, and chrome. Each metal was selected on the basis of its nontoxic status, suitability for contact with human skin and mucous membranes, its ability to be electroplated, and the ease with which it could be sterilized.

The experiments

Unlike the tuning fork encounters, the spoons investigation was staged as a formal scientific study (Laughlin et al., 2011). The spoons were presented for encounter in order to gather data on the human experience of the taste of materials that could be mapped against the standard electrode potential of the same materials. We recruited 32 participants of mixed ages and both genders. Participants were blindfolded and asked to taste each spoon sequentially, rating each one on scales of 1–7 for the adjectives cool, hard, salty, bitter, metallic, strong, sweet, and unpleasant. The subjective experiential data were analyzed using standard statistical techniques. In brief, repeated measures one-way analysis of variance (ANOVA) with Tukey's Multiple Comparison Test was performed. For testing the order effect, which was considered undesirable (and therefore was sought with greatest power possible) in

FIGURE 4.2
The swatch of spoons used in the experiments. From left to right: copper, gold, silver, tin, zinc, chrome, and stainless steel. *Laughlin, 2010.*

addition to the Tukey comparisons from the ANOVA, the planned analysis included individual participant's paired *t* tests comparing the first spoon, which was always stainless steel, to the other stainless steel spoon, which was randomized in the order (Laughlin et al., 2011).

The results

Plots investigating the correlation between the perceptions and the relevant physical or chemical property of the pure metals (Laughlin, 2010; Laughlin et al., 2011) were obtained using standard physical and chemical data sources (Atkins and Jones, 2005; Latimer, 1952; Vanysek, 2009). For copper and gold, the electrode potential of two oxidation states were plotted since both could be formed in the mouth. For the adjective metallic, an inverse correlation between the electrode potentials of metal ions and perceived metallic taste of the metals was observed. An identical pattern was observed for the adjective strong. For this reason, zinc and copper were considered as strong tasting, while the other metals were considered mild tasting. A near-identical pattern was seen with the adjective unpleasant, with the minor exception that the difference between silver and either copper or zinc was not as significant: silver was not significantly more unpleasant than the other mild-tasting metals. None of the metals differed significantly in saltiness or sweetness.

The experiment revealed that more negative standard electrode potentials correlated strongly with perceived tastes of solid metals described as metallic, bitter, and strong, with an inverse correlation. The zinc and copper spoons rated highest for bitter, metallic, and strong descriptors, while the gold and chrome rated as the most pleasant tasting spoons. When putting these spoons in the mouths, the participants often commented on how they liked them, or at least noted the absence of taste. Gold was determined to be the least strong tasting, followed closely by chrome, but chrome rated as being the least metallic, closely followed by gold. Finally, gold spoon emerged with the highest sweet rating of all the spoons.

It is commonly presumed that metallic tastes are unpleasant. In our taste study the descriptor metallic was statistically correlated with both the adjectives "unpleasant" and "strong", which indeed suggests that, when considering metal spoons, metallic taste is considered both strong and unpleasant. This raises the possibility that our measurements of metallic tastes, where gold and chrome were the least metallic, may correlate with preference for different metals, although this needs to be studied further.

The conclusion of the study was that the taste of solid metals is dependent on their standard electrode potentials. This is a concrete example of how a perceived quality (metallic taste) can be directly linked to a physical property (standard electrode potential).

CONCLUSIONS

The pertinent question to ask at this juncture is how can such information be used in a practical way? Our experiments demonstrated strong links between aesthetic qualities of material—objects and underlying engineering material properties. We have shown that the acoustic quality of tuning forks are correlated with their form and materiality, and we have shown that the intensity of metallic taste of spoons is dependent upon the standard electrode potential of the metals from which they are composed. To answer the question above, we come back again to materials selection. There are many tools to help designers and engineers choose materials with specific physical properties, which allows them to make informed choices before stepping away from the drawing board. When dealing with the sensoaesthetic properties of materials, choices tend to come down to experience, prior knowledge, and intuition, and there is no systematic way to approach such selections. A sensoaesthetic theory of materials may create such an opportunity, allowing designers, engineers, and artists to make informed decisions on aspects of their designed object's properties, both physical and sensorial. However, to date there has been relatively little research activity in the study of the sensoaesthetic properties of materials within the materials science communities (Miodownik, 2007). It can be argued that materials science, as an academic research discipline, is somewhat estranged from the materials arts communities who are experts in and enthusiasts for the aesthetic, qualitative, and sensorial qualities of materials. Additionally, as the study of sensoaesthetics is not quantitative in the same way as more familiar physical studies are (it involves psychophysical methodologies along with physical analysis), such studies are perceived to be detached from materials science. However, we strongly believe that this space between materials science and materials arts is fertile ground, and that new and exciting approaches can be adopted for producing pieces of work and objects that are as sensorially considered as they are technically advanced.

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CHAPTER 5

Manipulating the Material Code: The Transformation of Material Meaning in Contemporary Japanese Design

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CONTENTS

Materiality not only influences the physical attributes of objects and environments, but also shapes experience. In design, each material decision is charged with meaning, and materials convey particular social, historical, and technological information. Sophisticated designers recognize that this embedded information can be used to elicit particular responses from a viewer, based on his or her prior set of experiences. The process of manipulating this material code for positive effect is a critical stage in the achievement of design innovation.

Japanese design is a particularly important sphere in which to study material applications, due to the high level of craft and material mastery demonstrated by Japanese designers. For many practitioners in Japan, technical acuity is accompanied by a sophisticated understanding of sensory perception. Kenya Hara, founder of the Hara Design Institute and art director of MUJI, calls this experiential knowledge *information architecture*. To Hara, design does not result in a physical artifact so much as a cognitive experience: "A designer creates an architecture of information within the mind of the recipient of his work. Its structure is comprised of the stimuli that enter through assorted sensory perception channels. The stimuli, which are brought forth by the senses of sight, touch, hearing, smell and taste and various aggregates of these senses, are set up in the brain of the recipient and there emerges what we call 'an image'" (Hara, 2007a).

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Materiality is fundamental to the construction of this image. Influential material attributes include not only form, texture, color, and other physical qualities, but also the material history of an object and its means of production. According to Japanese architect Jun Aoki, "A material is perceived according to a code—a social code. And so we can manipulate the code itself" (Jun Aoki quoted in an interview with Blaine Brownell, 2011). For Aoki and many of his Japanese contemporaries, this act of modifying a material in order to change the way its related semantic information is perceived is a critical step in the design process. Such a change requires an astute knowledge of Aoki's *social code*—which we might define as a collectively shared lexicon of experiential knowledge—that colors how audiences perceive a new design.

Since the publication of Roland Barthes' *Mythologies*, the field of design semiotics has revealed the complex dimensions of communications in product design. Scholars such as Reinhardt Butter, Klaus Krippendorf, Rune Monö, and Susan Vihmas have furthered our understanding of product semantics by the development of sign system classifications and analyses of the ways in which various symbols and icons are perceived. According to design scholar Sara Ilstedt Hjelm, design semiotics posits that "meaning is not 'transmitted' to us [by products] — we actively create it according to a complex interplay of codes of which we are normally not aware" (Hjelm, 2002).

For many Japanese designers, enhancing user awareness is a necessary part of creating memorable and significant works. In this chapter, I will consider Japanese designs that strive to increase user awareness through intentional shifts in material usage. I will explore five methods of material manipulation—each of which involves a different strategy to influence user experience—that are actively employed by a collection of eminent Japanese practitioners. These methods are used to transform particular dimensions of material knowledge as the primary means of elevating user consciousness.

SENSORY MANIPULATION

The manipulation of reality is a potent strategy for engaging user consciousness. According to Japanese architect Kengo Kuma, "Reality is only truly perceived in the presence of some unreality… If [a design] is a little unreal, there is a little bit of a surprise. If there is no surprise with something, it is not real, because it goes unnoticed. It might as well not exist" (Kengo Kuma quoted in an interview with Blaine Brownell, 2011). For Kuma, distorting reality is key to eliciting user response. Like optical illusions that employ deceptive approaches to visual communication, Kuma's manipulation of reality is intended to make users conscious that they are being tricked without the illusion falling apart—a phenomenon called *cognitive impenetrability* (Pylyshyn). The strategy of sensory manipulation distorts materiality to deceive and provoke one's senses simultaneously. It engages a user's knowledge of the physical world, and encourages him or her to question the physical behavior of matter.

This approach is immediately evident in the work of designer Oki Sato. Founder of the multidisciplinary design firm Nendo, Sato continually evokes what he calls "a small '!' moment"—which is a subtle, yet still noticeable surprise. Sato's specific aim implies a finely tuned strategy of sensory modification, dialed in just above a user's conscious threshold. Nendo's X-Ray Vase developed for Lasvit in 2012 is an example of sensory distortion via the use of complex optical effects. The vase is a glass dome occupied by multiple, smaller glass domes. Although the glass is transparent, a thin, vapor-deposited mirror coating greatly

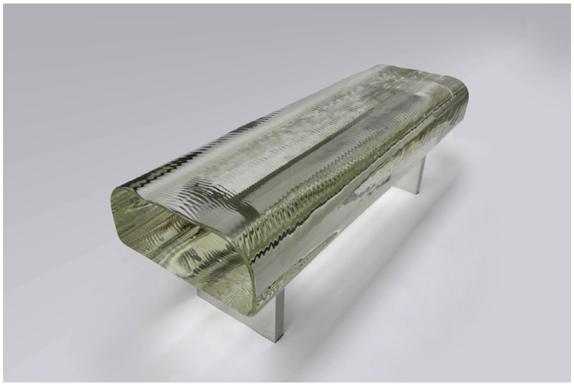

FIGURE 5.1
Water Block, Tokujin Yoshioka.

increases the visual complexity of the glass' geometry. According to Sato, "When flowers are placed inside, the glass and flowers are reflected diffusely over and over, creating an optical effect in which flowers and domes are both hidden and visible" (Sato, 2012a). In this way, the material characteristics of transparency and reflection are combined in a delicate balance, resulting in a vessel that allows clear views into what appears to be a much more voluminous space than exists.

Designer Tokujin Yoshioka has also explored various optical effects enabled by transparency and reflectivity, exemplified in his Water Block bench and Chair That Disappears in the Rain (Figure 5.1). Both furniture designs feature solid slabs of glass that are cast with a rippled surface. This precisely controlled texture is intended to emulate the animated surface of water, preserving the glossy transparency of the glass without any discernible repetition. Like small waves in a pool, the ripples allow views while simultaneously distorting them. In this case, the surprise results from Yoshioka's embodiment of what appears to be a liquid state within a solid material (see also quasi-mimesis, below).

In addition to reflectivity, Japanese designers experiment with other means of achieving optical distortion. For the Illoiha fitness club in Ebisu, Tokyo, Nendo employed a special view control film that makes light behave in unexpected ways. When observed straight-on, the film appears transparent, but is translucent when viewed from other angles. Sato applied the film to the ceiling of a 50-m-long corridor, with the intent to create an unusual experience in what might otherwise be a monotonous space. By layering a patterned, light-transmitting textile against the film, Sato created a luminous horizontal plane that reveals small details above the visitor while becoming ghostly and inscrutable beyond this narrow view angle. "We thought we'd take a material ordinarily used to hide things that we either don't want to see or don't want to be seen, and to use it to show something off instead," says Sato (Sato, 2006).

QUASI-MIMESIS

As Yoshioka's waterlike glass furniture demonstrates, the mimicry of natural substances is another method employed to transform material meaning. Yoshioka calls the embodiment of natural phenomena in designed objects and environments *second nature*. It is important to note that this type of approach is not pure mimicry, as seen in faux materials. As the term *quasi-mimesis* suggests, the method involves a *partial* emulation of one substance in another. The designer of quasi-mimetic objects intentionally borrows a foreign material language while simultaneously revealing its improbability. Like optical illusions, the goal is another kind of cognitive impenetrability: rather than simply deceive the user, the designer seeks to spark interest by subtly revealing this slight-of-hand maneuver. This approach engages a user's knowledge of the natural world, prompting him or her to question the true material nature of things.

Designer Naoto Fukasawa is adept at quasi-mimesis, demonstrating how even simple, everyday objects may be imbued with "a quality to shake us back to our senses" (Naoto Fukasawa quoted in Naoto Fukasawa and Jasper Morrison, 2007). This quality results from the shrewd combination of two dissimilar material languages in a way that allows their original identities to remain intact. Fukasawa's Juice Skin is a compelling example of quasi-mimesis (Figure 5.2(a)). Developed for the Haptic exhibition held in Tokyo in 2004, Juice Skin consists of juice boxes that appear to be wrapped in the actual skins of the fruit whose juice they contain. When first seen, the effect of the juice boxes is immediate: audiences quickly comprehend both the contents of the objects as well as the pun Fukasawa is making, since the use of actual fruit skin would be unworkable for this application. Borrowing the precise Japanese craft of simulation developed to make fake plastic food for restaurant displays, Fukasawa creates vividly realistic surfaces that conform to the improbable geometry of disposable beverage containers.

While Fukasawa's juice cartons evoke delight, other quasi-mimetic objects venture into less comfortable territory. Created for the same exhibition, fashion designer Kosuke Tsumura's Kami Tama presents the

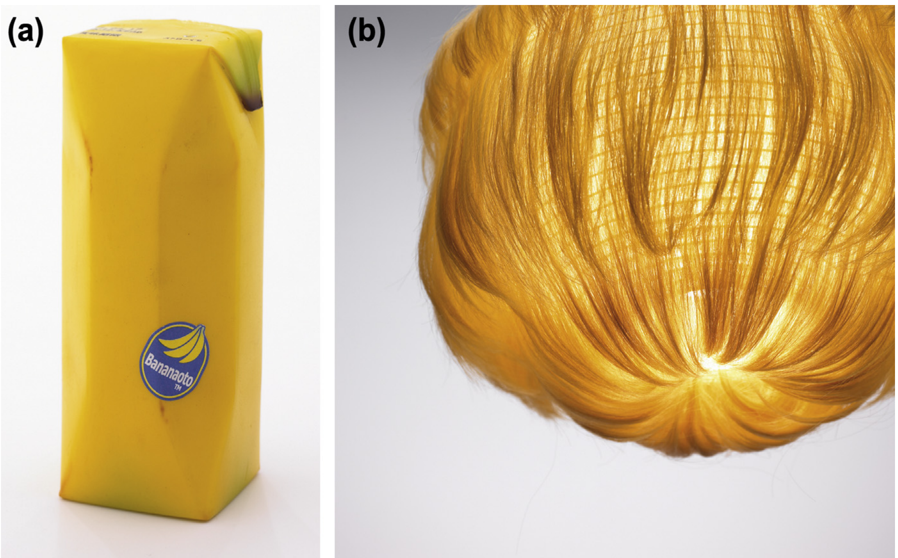

FIGURE 5.2

(a) Juice Skin, Naoto Fukasawa. Direction: Kenya Hara, (b) Kami Tama, Kosuke Tsumura. Direction: Kenya Hara.

uncanny marriage of paper lanterns and human hair (Figure 5.2(b)). The lanterns' fabrication required the painstaking labor of wigmakers, who attached the hair to silk-backed paper using traditional hair implanting technology. The suspended objects, which conjure faceless, floating heads, have inspired the nickname "devil lanterns" (Hara, 2007b). Similarly uncanny is the No Constraints Carpet developed by Panasonic Corporation for the Tokyo Fiber exhibit in 2007. The product is a kind of electrically heated body warmer, designed to mimic the furry pelts of animals. Also notable is a "prickly" logo that Kenya Hara created with animal hair on silicone.

As these hairy, zoomorphic designs demonstrate, quasi-mimicry can be used to challenge a user's comfort level. However, the approach may also be used to conjure other varieties of natural materials. One example is Nendo's Lacquered Paper Objects, developed for Nilufar in 2012. At first glance, one might imagine these small rounded containers to be made of a darkened, burnished wood. In reality, the delicate objects consist of hundreds of sheets of industrially produced paper, which are layered, cut, and glued together with the use of a three-dimensional (3D) printer. Nendo coated the objects with lacquer, noting that "the lacquer adhered thickly to the edges of the accumulated paper, and pulled at the paper's surface, resulting in a mysterious texture like wood grain" (Sato, 2012b). Compared with the previous examples, this approach is much more subtle—yet no less captivating. Upon close inspection, the lacquered containers reveal a grain of uncanny precision, radiating from a perfectly aligned center like growth rings in miniature, elliptical trees.

TRANSLITERATION

The act of borrowing an unexpected design language as a way to shift material meaning extends to the realm of functional objects. Just as quasi-mimesis introduces an unanticipated material vocabulary from the natural world, *transliteration* co-opts material language from the world of industrial objects. Similar to the other strategies, the effect of transliteration is often disarming for the user. It directly engages its audience's knowledge of designed objects, calling into question the nature of function itself. Hara addresses the spirit of this approach in a description of geometric "tweening" between two different functional objects.

For example, imagine a plate and a cup. A plate and a cup are clearly different from one another in shape, right? If the cup gradually becomes shallower and wider, however, it approaches the shape of the plate. Now imaging a subtle gradation from cup to plate. Try to establish a boundary between the two. At a certain point, we do not know if we are looking at a cup or a plate. This new form of ignorance actually results in a better understanding of what makes a cup a cup and a plate a plate. In daily life, we assume we know what a cup and plate are without a doubt. Yet, this little experiment surprises people. Rather than making an amazing form for a cup, it is more effective to explore the gradient between a cup and a plate. In this way, people will realize how much they do not really know. This is beautiful design (Kenya Hara quoted in an interview with Blaine Brownell, 2011).

While transliteration sometimes involves this kind of incremental gradation, dissimilar design languages may also be combined in less rigorous ways. However, Hara's explanation establishes the rewards inherent in designing in a more fluid manner, free from the widely held preconceptions that limit formal and functional possibilities.

One of the most beloved transliterated objects is Fukasawa's wall-mounted CD player. Designed for MUJI in 1999, the device takes direct inspiration from a wall-hung sconce. Fukasawa's unlikely provision of a drawstring as the primary control interface is clearly a reference to electric lighting—indeed, what other CD player is controlled by such a mechanism? The incorporation of an audio speaker uniformly within a simple casing furthers the analogy to a dimensional sconce, giving the object substance without visual clutter. Fukasawa's design is simultaneously foreign and familiar—an unusual format for an audio device, but a welcoming format for a pull-string appliance.

A more recent example of transliteration is Takeshi Miyakawa's Holey Chair (Figure 5.3(a)). The object is really not a chair at all—a fact reinforced by its lack of a seat—but rather a light fixture that borrows the iconic form of a chair. Made of translucent white acrylic with embedded interior light-emitting diodes (LEDs), the design glows homogeneously from within. While the placement of the Holey Chair in a conventional position on the floor might not immediately turn heads, its location on a wall or lamp post is certainly unexpected. Other light fixtures that adopt the language of unanticipated objects include Midori Araki's ceramic Bottle Light, which alludes to a dishwashing soap bottle, and Kouichi Okamoto's Bulb Lantern, which refers whimsically to preelectric Japanese paper lanterns (Figure 5.3(b)).

Another form of transliteration involves the literal borrowing of unanticipated objects. Kouichi Okamoto's Water Clock is a simple rectilinear ceramic stand that requires the use of a plate and glass to function. The user places the necessary dinnerware on the device, filling the pieces with water and two supplied metal spheres. Embedded magnets within the clock base rotate throughout the day, moving the different colored spheres according to the current hour and minute settings. This do-it-yourself example expands the expected functionality of dinnerware, revealing new possibilities for these everyday objects.

REPURPOSING

Just as Okamoto's clock makes use of objects not typically seen in timepiece design, the strategy of material *repurposing* involves the use of one material for another, unexpected function. While

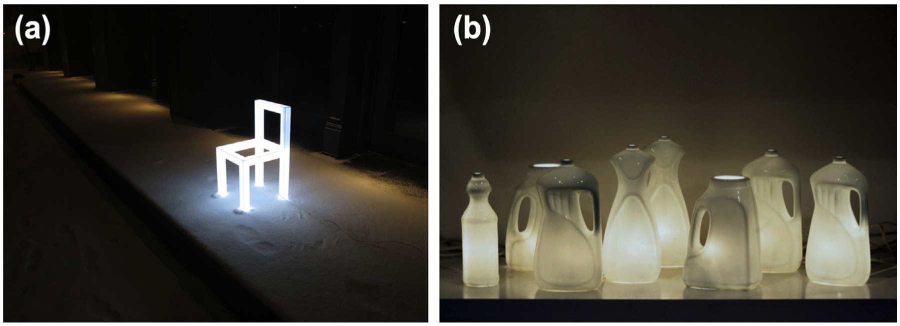

FIGURE 5.3
(a) Holey Chair, Takeshi Miyakawa; (b) Bottle Light, Midori Araki.

transliteration shifts a functional product's expected physical design, repurposing subverts the expected use of a material or process. Repurposing engages the user's knowledge of industrial production and material craft, inviting him or her to question a material's anticipated application.

Developed for the Carpenter's Workshop in Paris, Nendo's Farming-Net Collection is a series of containers made from agricultural nets. Although the mesh material is typically used to protect vegetables and fruit from pests and wind, Nendo has found that it serves as a workable substance for making products like bowls, vases, and hanging light fixtures. "The nets are stronger than organdy but more flexible than wire mesh," says Sato. "Using them as a sculptural material allowed us to evade the traditional necessity of combining structure with a separate surface material, to create a thin membrane that stands independently, but also floats gently on a breeze" (Sato, 2012c). Nendo's collection demonstrates how repurposing invites designers to think laterally, shifting material practices "sideways" from other industries or disciplines. In this particular case, Sato identified possibilities in the agricultural net material reminiscent of Japanese craft traditions such as *furoshiki* (wrapping cloth), *shibori* (tie-dying), and lantern paper. "The action of gently wrapping something and close attention to the texture of the surface endow these objects with the very particular sense of expression found only in Japan, since ancient times" (Sato, 2012c).

Another example of a repurposed material that conjures a particularly Japanese sensibility is Kouichi Okamoto's Honeycomb Lamp (Figure 5.4(a)). Made of *denguri* paper that is a local specialty from Japan's Shikoku region, the lightweight product comes flat packed with a thickness of only 2 cm. Its honeycomb construction allows it to be expanded and rotated to form the 3D profile of a classic table lamp with lampshade—a whimsical nod to an icon of traditional residential lighting. When pinned in this closed shape, the lamp and shade emit a soft, even glow, which is made possible by the diffuse optical qualities of the material.

Tokujin Yoshioka's Honey-Pop chair, comprising glassine paper and glue, makes similar use of honeycomb construction. Unfolded into its desired shape, the design is finally complete when the first user sits on the chair, making a permanent impression. Yoshioka's Pane Chair is similarly composed of a lightweight, homogeneous material (Figure 5.4(b)). In this case, however, what the designer repurposes is a material process. Inspired by bread baking—in which a soft, malleable material is given more rigidity

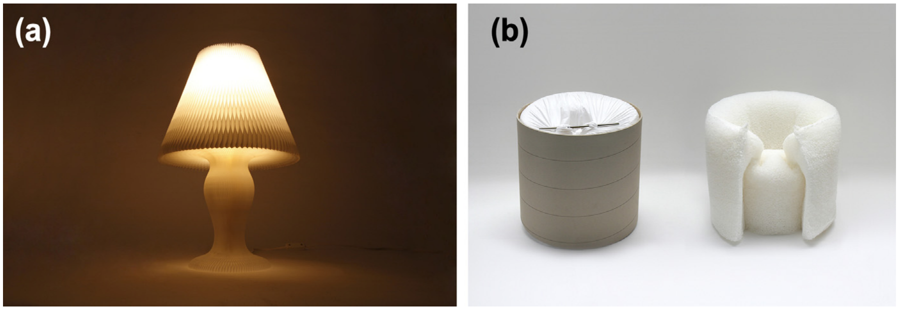

FIGURE 5.4
(a) Honeycomb Lamp, Kouichi Okamoto; (b) Pane Chair, Tokujin Yoshioka.

and strength with heat—Yoshioka developed a process to bake a fibrous substrate into the form of a chair (*pan* means bread in Japanese). After being inserted into a protective casing and cooked at 104°C, the original foam material becomes firm enough to support a person's weight. The sensibility of using weak materials to create solid structures is a favored Japanese approach, inspired by natural examples. "If you look closely at plants, you will witness the accumulation of many fine fibers that create a strong network," says Yoshioka (Tokujin Yoshioka quoted in an interview with Blaine Brownell, 2011a).

Processes may also be borrowed from other disciplines to create new materials themselves. Textile designer Reiko Sudo of Tokyo-based Nuno frequently looks to other industries for ideas to inform the creation of new fabrics. In one material series, Sudo employed the process of sputter plating used by the automotive industry to create chrome-finished elements such as door handles and trim. Although the method was never intended for use on large, flexible surfaces, Nuno developed the application to coat polyester and other textiles with different metals. For another series, Sudo appropriated a technique she learned from cooking. The Burner Dye textiles feature stainless-steel broadcloth with burn marks made in a similar way that opalescent streaks form on steel pots when placed over an open flame.

AGGREGATION

Aggregation is used to shift material meaning in terms of quantity, scale, and character. In simple terms, aggregation involves the assemblage of multiple copies of an individual product or material. The transformation results with the shift in focus from the discrete unit to that of the field—from a singular object to an immersive surface or space. Designers who employ this method carefully consider the relationship between objects, their means of connection or adhesion, the disposition of interstitial spaces, the structural requirements of the assemblage, and the metageometries that materialize as a result of these detail-level decisions. Aggregation harnesses the potent sensory effects made possible by a particular form of visual complexity, which is the intricate and multifaceted collection of self-similar components. The resulting field exhibits the properties of emergence, conjuring memories of immersive natural phenomena that lead to rich and varied experiences. In this way, aggregation engages users' embedded visceral knowledge of the natural world, and invites them to question the boundaries between object and field.

Tokujin Yoshioka actively exploits the sensory potential of material aggregation in his work. In his 2006 Remembrance window display at Maison Hermes, Yoshioka amassed thousands of translucent drinking straws, arranging them horizontally at varying depths to create the illusion of jagged cloud formations (Figure 5.5(a)). In his design for the Swarovski Ginza facade, he arrayed chrome-plated hexagonal pipes vertically, such that their bottom profiles were suspended in a precarious fashion above the shop entrance. In both installations, Yoshioka capitalized on the visual richness that can result from the assemblage of multiple, identical elements.

In a similar fashion, Kouichi Okamoto transformed the common balloon into an elegant chandelier with his Bekkou Balloon Lamp. Inspired by the traditional *cochin* lanterns of Edo-era Japan, Okamoto used white LED lamps in place of candles and inflatable rubber balloons instead of paper. Like Yoshioka's accumulation of drinking straws, this visually arresting assemblage illustrates the transformative potential of aggregating inexpensive, disposable consumer products.

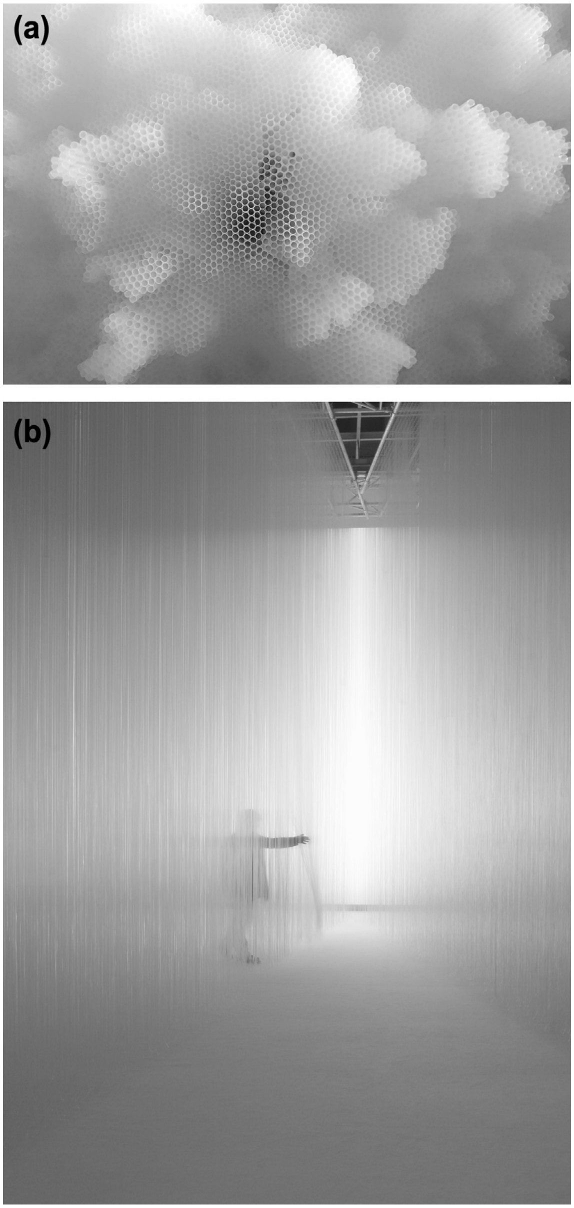

FIGURE 5.5
(a) Remembrance window display, Tokujin Yoshioka. Photo: Blaine Brownell. (b) Lexus L-Finesse, Tokujin Yoshioka.

In addition to surfaces and free-standing objects, aggregation is an important means to construct immersive environments. In the L-Finesse exhibit for Lexus, Yoshioka collected some seven hundred kilometers' worth of optical fiber and suspended it from the ceiling of a bare, white interior (Figure 5.5(b)). Although optical fiber was never envisioned as a spatial medium, the powerful atmospheric qualities evoked by Yoshioka's foglike installation demonstrate the capacities of aggregation to transform an individual product into a completely new experience. Despite the synthetic nature of the exhibit, Yoshioka tried "to create experiences that related to viewers' deeply embedded memories of previously witnessed natural phenomena" (Tokujin Yoshioka quoted in an interview with Blaine Brownell, 2011b).

Artist Shinji Ohmaki makes similar use of suspended white string in his Liminal Air installation. In this case, however, the fibers do not touch the floor. By changing the length of the strings, Ohmaki created an undulating, inverted topography that welcomes audiences into its billowing contours. Artist Yasuaki Onishi likewise projects a rippling surface with his Reverse of Volume RG installation. For this work, Onishi attached thousands of strands of black-dyed hot glue to a translucent sheet that was draped over removable formwork. The resulting environment demonstrates a phenomenon he calls "casting the invisible", creating a palpable manifestation of negative, or void, space.

CONCLUSIONS

These examples demonstrate how several renowned Japanese designers use sensory perception as a primary driver for design. Although design is a well-established discipline globally, the role of user awareness in the experience of design is not well understood. In his book *Massive Change*, Bruce Mau makes the provocative statement that "the secret ambition of design is to become invisible, to be taken up into the culture, absorbed into the background" (Mau and Leonard, 2004). Presumably, Mau's polemical viewpoint is aimed at the comprehensive world of synthetic objects, most of which do not invite much attention beyond communicating their practical use. The counterargument to this perspective is that design's mission is actually to be visible, to provoke consciousness, to be foregrounded. In the view of the practitioners described above, design is not merely a technical practice that seeks to fulfill a need, but rather an enlightened discipline that also makes meaningful contributions. Instead of an involuntary or naive practice, design is imbued with an educated awareness of its audience, based on insightful knowledge about users' past observations. As such, the material presence of design becomes a critical concern, due to the meaning imparted by materials to human experience.

We may relate the user experience of design to the process of learning, insofar as both activities are intended to enhance human capacity and knowledge. In the book *Communities of Practice*, educational theorist Etienne Wenger declared that the difference between learning and rote action is that "learning—whatever form it takes—changes who we are by changing our ability to participate, to belong, to negotiate meaning" (Wenger, 1999). The argument that learning inherently transforms its audience may also be applied to the experience of design. In order for such a change to occur, the user must become aware; an observed design must establish a presence within his or her consciousness. We could therefore say that the designers presented here are not motivated so much by the design of objects, but by the "design of the senses"—borrowing Kenya Hara's description for "the creative awakening of the human sensors" (Hara, 2007c).

Although this chapter focuses on Japanese design, the methods presented here are not exclusive to Japanese society. Rather, they are intended to demonstrate the extent to which intentional shifts in the "social code" of materials are a fundamental part of the design process. It is my hope that by understanding the mechanics involved in creating objects and spaces that enhance user experience, designers from any region can make more compelling, memorable, and innovative designs.

Acknowledgments

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CHAPTER 6

The Immaterial of Materials

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CONTENTS

I recall a lecture I once attended as a first year design student on the selection of metals for design projects. It was memorable in the way it was delivered, and the key tenet of the lecture remains still. "In all cases use steel", the lecturer said before gesturing to leave the room … "oh, except if you need it to be lightweight, then you should use aluminium". He then left the room leaving my fellow students and me somewhat dumbfounded. Was that it—a supposedly hour-long lecture reduced to one sentence? The lecturer returned after just long enough for the idea to sink in. He continued the lecture, "oh, unless you need it to be really lightweight, and then you use magnesium", and then outlined more exceptions to this simple "rule" of materials selection. The lecture had a profound effect on me. It was certainly an invaluable way of thinking about materials selection, but it left me insatiably curious about the choices we make when selecting materials—was that all there was to it? Do not get me wrong, I am in no way critical of the lecture or its message—far from it, for the simple elegance of this approach to selecting materials based upon their performance characteristics relative to their cost has helped construct the way I think about and select materials—but the thought that there must be more to material selection, and at what cost we select materials has remained with me ever since.

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AESTHETICS AND ETHICS: REFLECTIONS ON PERSONAL TASTES AND MATERIAL PREFERENCES

Perhaps the most obvious example of where the rationality of choosing materials based upon performance and cost is not so clear-cut (forgive the pun) would be the selection of timber. Timber's color, figure, smell, texture, and so on help inform our aesthetic preference—we may prefer lighter colored woods than darker ones, or we may like the smell of cedar or sandalwood, or we may like the simplicity of straight-grained timber or the more complex figure of a burl wood. Our "tastes" are not solely based upon such sensorial stimuli, but also on an emotional and cultural connectedness to the material.

Timber speaks of its geographic origins; be they native or exotic, we associate certain woods with their traditional location as embodied in vernacular architecture and furniture. Furniture and building traditions have utilized locally sourced materials, and hence there is cultural association of particular woods in particular parts of the world: oak is to England as eucalypts are to Australia, for instance, and Scandinavian furniture is exemplified in its use of light-colored straight-grained timbers such as spruce and birch.

The popularity of Scandinavian design is of course global, but our choice of selecting one timber over another, when both exhibit similar physical properties can come down to not only our aesthetic preference but also to our cultural heritage and association of the material with our sense of history and place. This personal aspect of materials selection is important to acknowledge, but our aesthetic preferences are also being modified—or recoded—as we become increasingly aware of environmental concerns such as overlogging, destruction of native forests, and the depletion of biodiversity caused by the globalized nature of timber plantations.

European colonization of the world brought about the export and import of native and exotic timbers, and wooden furniture manifestly expressed the extent of empire in the wide range of woods used in cabinet making. Indeed wooden marquetry work from the sixteenth to eighteenth centuries unashamedly flaunted this, and thus began the incredible exploitation of timber resources across the globe. It was not just timber that was the spoil of colonial exploration and exploitation—many material resources were harvested and extracted from around the globe, and the exploitation continues today, but is somewhat less conspicuous.

AT WHAT COST?

I am typing this chapter on my iPad on my kitchen table. Coffee in hand, I have the weekend paper before me. There are the usual news stories—a war criminal prosecuted, political ranting about carbon taxes, a story on global warming, someone has died of mesothelioma, commodity prices are up, a major company is recalling toys after lead was found in the paint, and a jewelry store is having a half-price sale. But what is this all got to do with selection of materials? Unfortunately, a great deal.

Tucked away in the World section of the newspaper, there is an article about the Democratic Republic of Congo (DRC) and talks of the jailing of a warlord over the conscription of child soldiers, and of genocide and atrocities over the mineral riches of this region of Africa. As I read, I am making the connections and links back to my own purchases and my own decisions to use certain materials in my designs and I am shocked by how much I did not know.

The paper refers to an older Amnesty International Report that I duly download and read on my iPad.

> Four years of conflict in the Democratic Republic of Congo (DRC) have proved among the most disastrous in the history of modern Africa. Some three million people are believed to have lost their lives and more than two-and-a-half million have been driven from their homes, 500,000 to neighbouring countries. … Thousands of Congolese civilians have been tortured and killed during military operations to secure mineral-rich lands … Children as young as 12 have been among those forced into hard labour in the mines. … The ambition of all these combatant forces to exploit eastern DRC's mineral and economic wealth has been the biggest single factor in the continuing violence.
>
> **(Amnesty International, 2003, pp. 3–4)**

The article lists the mineral wealth of the region: timber, oil, gold, diamonds, coltan, copper, zinc, wolfram, and coffee, to name a few. Some of these materials I was not aware of, nor what they are used for. I let my coffee go cold as I read on, "International commercial interests in coltan, gold, diamonds, timber, and other precious resources have, knowingly or unknowingly, contributed to human rights abuses" (Amnesty International, 2003, p. 5).

I begin to question where all these materials end up and what my role in all this might be. For some years now I have been aware of the Forest Stewardship Council and its role in certifying timber to ensure it comes from a well-managed forest or plantation, and will only purchase timber that has this international certification. I also buy Fairtrade coffee, but as for the other resources on that list I begin to realize I just do not know where the materials around me have come from.

Coltan, or colombo-tantalite, is an ore rich in niobium and tantalum. Niobium is typically used for high-performance alloys and superconducting magnets used in such things as magnetic resonance imaging scanners. Tantalum is used to produce tantalum electrolytic capacitors used extensively in mobile phones, computers, and consumer electronics. These capacitors are expensive but their value is in how lightweight they are compared to other capacitors and, with the drive to ever-smaller devices, the demand for tantalum is high. Indeed, the price of tantalum well over doubled in one month from $87/kg in May 2012 to $215/kg in June 2012 (InvestmentMine, 2012).

I look at the iPad and my mobile phone next to the newspaper. On the reverse of the iPad it says "Designed by Apple in California. Assembled in China". This is a powerful statement, and celebrates the importance of design to the Apple brand. Competitor products typically just state where they are made. As I question where the tantalum in my iPad, my mobile phone, my laptop, and countless other devices came from, I wonder whether we perhaps need to see three levels of design and manufacturing information on the labeling of our products: where it was designed, where it was manufactured or assembled, and from where the materials were sourced. This third level would be problematic to implement on several counts—the sheer number of materials in some products would render this unmanageable—but this is an important bit of information left out of the loop that could go some way to helping us make more responsible choices.

At what price love? The noble and ignoble story of the wedding ring

I retrieve the jewelry catalogue I had discarded in the recycling bin; a major jewelry store is having a half-price sale. It describes the prices as "slashed", "cut", and "once in a lifetime", the jewelry as "hot" and "stunning", and it states that "you'll turn heads" wearing "this season's must haves", and "you'll be hooked on these new and exclusive collections" (exclamation marks removed). In the light of reading the report from Amnesty International, somehow all the adjectives in this punchy advertisement seem quite perverse—a truism perhaps. That precious gift is now much cheaper, but at what cost in human terms?

Consider the symbolic and monetary value of a wedding or engagement ring. Most commonly the wedding ring is a simple band of gold (or other expensive material). The monetary value associated with the ring, in times past, was very significant (an endowment), and the embodiment of value and inherent symbolic meaning of the material in being noble (resistant to corrosion and oxidation), its longevity, and indeed its rarity established gold as the material to signify marriage. But let us consider modern gold (Larmer, 2009) and diamond (Global Witness, 2011) mining practices, and the environmental, political, and human costs associated with their extraction: far from being noble, there is an ignoble side—in parts of the world the story of gold and diamonds is one of human violation (childhood slavery and blood diamonds), environmental pollution (arsenic leaching into rivers killing fish stocks), and corruption (money laundering and weapons trading). Is this how we should symbolize love?

One of my Industrial Design students, Edward Sackett, took this question on as his final year Honours project, where he set out to design and make a series of alternative wedding rings to the traditional band of gold. Two of Edward's designs for these rings are described here and shown in Figure 6.1. The inherent value embodied in the design of the rings was achieved by two very different approaches to material selection; one material was rare and endangered, the other very common.

The first ring, *Hou Ola* (Hawaiian for "new life"), is made of bronze and wood from the endangered Hawaiian native Koa tree (Figure 6.1). As Edward describes, "The wood used in this ring comes from sustainable plantations where some of the profit from each ring is invested in planting a Koa tree. The planting of this tree is a physical metaphor for the beginning of the new life/journey for a newly wedded

FIGURE 6.1
Wedding rings by Edward Sackett (2009). (a) Hou Ola, (b) Semper Amemus.

couple. The non-polished bronze becomes shinier over the years from being worn by the user, which represents the beauty of a growing relationship. Each set of wedding rings is made from the same piece of wood, which signifies a couple's unity" (Sackett, 2009). As the pair of rings is machined from the same piece of timber, the unique figure of the timber is congruous to both rings, with the grain of each ring aligning with its partner to symbolize the unique unity of the wedded couple.

The second pair of rings, *Semper Amemus* (Latin for "forever in love"), are simple bands of ferritic stainless steel with the couple's fingerprints etched into the steel—each ring carrying the partner's "touch". The pair of rings is magnetic and, as Edward explains, "The magnetic properties of Stainless Steel F430 used in the bands symbolise the attraction and unity shared between two lovers." The *Semper Amemus* ring presents a lovely proposition—that the value of the ring is not so much in the *material* worth but in the *immaterial* worth—the symbolism and meaning inherent in the ring is its richness and treasure.

Interestingly, there are also cases where the opposite is true—that is, the material itself is not valued. Let us consider the case of packaging.

On valuing materials

I used to present a lecture where I would hand out a few empty margarine containers that I had rescued from the waste bin and a pair of sunglasses by a leading fashion brand, and asked the students which was the most valuable. Not surprisingly, the sunglasses always won out, with a price tag of well over $50, the answer seemed obvious. However, weight-for-weight, the margarine containers are made from a more expensive and higher quality material—food-grade acrylonitrile butadiene styrene (ABS)—than the sunglasses, which were made of a standard-grade ABS, and cheaper styrene blends. Yet the margarine containers were discarded without much thought, and were deemed to be of no value.

Packaging consumes more plastic than any other industry at 39% of the total use of plastic; by way of contrast, this is seven times the volume of plastics used in electrical and electronic goods industries. Production of plastics has also grown on average nearly 5% per year over the past 20 years or so, with 265 million tons produced globally in 2010. Much of this plastic ends up in landfill; the exact percentage is hard to determine, and varies widely depending upon who provides the information, but the European Association of Plastics Manufacturers reports recycling rates of between 15% and 30% (Plastics Europe, 2011), with other sources quoting much lower than this.

This is a significant problem—not just from an environmental perspective, but from the social and cultural perspective of not valuing these materials. Other materials used for packaging, such as glass, paper, aluminum, and steel have far higher recycling or recovery rates (recycled at waste-recovery centers prior to going to landfill) than those of plastics. What is curious is that the use of plastics for packaging has, in part, devalued the perception of the material and the overpackaging of goods combined with our very systems of waste management (curbside collection of rubbish) has reinforced this thinking.

Since the first time I gave that lecture, I am now at least retrieving the margarine containers from the recycling bin rather than the waste bin, but the same issue remains, that we do not see the inherent value in the material.

For me, this example highlights the power of design to transform and embody value in artefacts, and reveals two compelling lessons:

1. the importance and value of the role of design in adding value and meaning to materials and conversely
2. that design can also contribute to the devaluing of materials—by excessive packaging and the encouragement of a throw-away society.

Changing perceptions: the curious story of cork and aluminum

Material perceptions are curious things indeed, and notions of social and cultural meaning, habitual behavior, nostalgia, prestige, and so on, all come into the mix in forming our perceptions of materials. Increasingly, the environmental impacts of materials—their ecofootprints as it were—are becoming part of the lexicon of consumers and designers. One curious example is the debate of the use of cork versus aluminum screw caps to seal wine bottles. Without going into the functional or emotional debate regarding which is better for the wine or the consumer, the environmental debate is interestingly contentious. The majority of Australian wines now use screw caps rather than the traditional cork. Cork is harvested form the *Quercus suber* oak tree, by peeling away the cork bark. Because the trees are not cut down in this process they continue to absorb CO_2, thereby helping to offset any carbon-emissions in the processing of the cork products. Conversely, in the production of aluminum screw caps, the CO_2 emissions are much higher (in the order of four times as much). Aluminum, however, is produced locally, whereas cork is imported from the other side of the world; hence, the CO_2 emitted in transporting the corks should also be factored into the ecofootprint. Then, considering that the bottle with the cork in is often wrapped in an aluminum foil anyway, the environmental argument can become a little academic. In short, there is always more than one argument to support the selection of one material over another.

The embodied energy in aluminum

The discussion of the ecological virtues of one material over another can be contentious, and aluminum presents another interesting case—where the aluminum is sourced from has a great impact on the material's ecofootprint. To produce aluminum, an incredible amount of electricity is required—indeed, at the beginning of 2012 there were six aluminum smelters in Australia and combined they reportedly consumed 15% of all of Australia's electricity (Keane, 2012). Five of these smelters use electricity from coal-fired power stations, while the other sources its electricity from hydropower; consequently the embodied CO_2 in the aluminum varies depending upon its source of manufacture.

MATERIAL AND MANUFACTURING LEGACIES

In the business section of the newspaper, there is a headline reading, "Kurri Kurri smelter closure to trigger 450 job losses". The smelter in the Hunter Valley north of Sydney will have significant impact on the community, with many other businesses in the area growing up around, and relying upon, this industrial base. The last few months have seen many headlines discussing the fate of the aluminum industry in Australia, with two other smelting plants having discussed closure, only to be "saved" by government bailouts. Without the government-funded rescue, hundreds of jobs would be lost, leaving communities devastated.

The decommissioning of inefficient, power-hungry, and highly polluting smelters in some ways is a good thing, but often whole communities and townships were built around these centers of work. When the smelter is no longer operating and the jobs are gone, communities can die, unless an alternative source of work is available. There are many stories of industries and communities dying, or else communities reinventing themselves when major employers move away from the area. Industrialized cities in the West (North America and Europe in particular) have seen tremendous upheaval as manufacturing heads offshore—be it the decline of the car plants in Detroit and Michigan, or the UK steel and ship building industries—the impact upon communities is majorly significant.

The dying legacy of certain industries—particularly manufacturing industries—forces change, and can reorient a community. It also necessitates those whose livelihoods have either directly, or indirectly, depended upon those industries to change the way they do things. For designers, this is very apparent where the globalized nature of material sourcing and manufacture has created greater complexity of the logistical management of the process of design and manufacture.

A painful legacy: from miracle material to mesothelioma

There are other legacies that some materials and manufacturing processes have left us with. There is a short article in the newspaper about another death from asbestosis, and a forewarning that many more people are likely to die from this dreadful and incurable lung disease in the coming decades. The length of the article is perhaps indicative that this has become an all too familiar story in Australia. Indeed, the UK and Australia have the world's highest rates of cancer deaths related to asbestos, and according to an article in the *British Medical Journal*, the peak of deaths is not expected until the end of this decade (Treasure et al., 2004). Asbestos is a naturally occurring mineral fiber that was used extensively after World War II, particularly in the construction industry, but also more widely as an electrical and heat insulator, for filters, and ship and car parts (brake pads, filters, and gaskets)- see Morris (2010) for an indicator of just how widespread asbestos use was in the automotive industry.

From the 1950s, many houses were constructed using asbestos fiber cement sheet, and the material was lauded as being a miracle material (see Bowley, 1960, for instance)—cheap; fire retardant; resistant to weather, fungal, and pest attack; moldable; light weight; and easy to work with. The latter point about being easy to use subjected many builders and home renovators to unsafe practices of cutting through and breathing in the harmful fibers. These very fine fibers are now known to be toxic, and tend to lodge themselves in the lungs where they can cause asbestosis (chronic inflammation and pulmonary fibrosis) and lung cancers, including a once rare lung cancer, mesothelioma.

The asbestos miners and their families constitute some of the most severely affected by exposure to asbestos. The story of one mine, Wittenoom in Western Australia, is deemed Australia's worst industrial disaster. The Mesothelioma Center states that, "Of the 7,000 individuals who worked at the Wittenoom mine from the 1930s until 1966, an estimated 10 percent have died or will die of mesothelioma. Today, the town has literally been wiped off the map, with only a handful of people remaining." (The Mesothelioma Center, 2012).

Asbestos appeared to be the perfect material to help build housing stock and rebuild nations postwar, but herein lies an important lesson of the potential dangers of economic and functional rationalism.

With hindsight, now that we know of the dangers of asbestos we utilize other materials, but there was significant evidence linking asbestos and lung diseases well before the mines ceased operation. Indeed, asbestos was still being specified for constructing homes until the late 1980s in Australia when it was finally banned in 1989. Other countries have also taken action to ban asbestos completely—the latest being Turkey in 2011. Throughout this time, however, and as argued in current legal proceedings, the asbestos industry knew of the dangers of exposure to this mineral, yet maintained their operations.

I turn to the automotive section of the newspaper to see this headline, "Chinese cars use asbestos in parts: Vehicle recall". Perhaps we have not yet learnt from history, with some manufacturers still using discredited practices.

Questioning color: I see red

Unfortunately, asbestos is not the only material whose painful legacy we must live with. There are many materials and processes once thought to be safe that, as time and our knowledge advances, we see in a different light.

The decision to specify certain colors for products appears an innocuous one, yet there are several examples of materials that are now banned from use in pigments and paints. As designers and manufacturers, we often specify colors, but do we actually consider what is in the pigments and paints we chose?

From a materials perspective, paint can be made up of thousands of chemicals, but primarily consists of pigments (the color), binders, solvents, and some other specialist additives such as ultraviolet stabilizers, biocides, emulsifiers, flatteners, and materials that create particular textures. The binder in the paint is typically a synthetic resin such as acrylic, polyester, epoxy, or an oil-based medium, and it is this material that adheres to the surface being painted and also constitutes the gloss level of the finish. The way in which these materials cure, or dry, is of note—many contain solvents that evaporate, and the solvents can pose a health risk. Solvents and other constituents of paint are often referred to as volatile organic compounds, and thankfully environmental legislation now regulates their use. Even so, paint can still contain hundreds of toxins and harmful substances.

There are many highly toxic materials that have been used to color our world. Take yellow, for instance. Sweets that can be fatal if swallowed sounds like the basis for a macabre tale befitting of Edgar Allan Poe, yet the reality is that up until the late nineteenth century, lead chromate was used to color confectionary bright yellow. We now know of the extreme toxicity of both lead and hexavalent chromium that constitutes lead chromate, of its carcinogenic properties, and that it can be fatal if swallowed or inhaled. Thankfully, Michael Vernon, the Australian consumer activist, campaigned for lead and cadmium to be banned from use in children's toys through the latter part of the twentieth century—we owe a lot to him, but still there are all too frequent violations.

When Mattel recalled millions of toys in 2007 because there was lead in the paint, it left them red-faced. It also colored our judgment of the safety standards in place in some manufacturing plants and begged the question just how many other toys went unchecked by toy companies with less stringent safety standards. The recall was costly, not only in financial terms; reputations were damaged too. But what could have been the cost in human terms if this went unchecked?

Lead is toxic—a poison that affects many body organs and interferes with the nervous system—and can lead to permanent learning difficulties, seizures, and even death. So what does lead do and why is it in paint in the first place? The answer is simply to add color—which is rather perverse considering that as designers we specify these colors to appeal to children, luring them to want to play with them, and in the process expose them to a potential killer toxin.

So the key question is how these toxic chemicals still end up in our toys and paint. The answer is unfortunately a product of the way in which design and manufacture has become a global business. One key reason why the majority of manufacturing has moved from the West to China, Southeast Asia, and parts of the developing world is the economic rationale that it is far cheaper to produce goods there. The reason for this, on the whole, is related to cheaper labor costs and scales of manufacture, but different labor and environmental laws between countries are also part of that equation. Environmental legislation is not necessarily binding or adhered to in all parts of the world, and certainly some countries have far more rigorous legislation than others and, conversely, some countries have none at all.

As designers we need to think very carefully about where our products are being made, and who is making key material and manufacturing decisions. We should question the underlying reason of why it might be cheaper to manufacture our products offshore.

CONCLUSIONS

This chapter has explored some of the lesser considered aspects of materials selection, and has questioned at what cost we, as both consumers and designers, select materials. The luxury of having choices comes with significant responsibility, yet we rarely consider or make explicit the connection between our material choices and the human and environmental costs our decisions may have. In many ways, the information about those connections is difficult to find, or else hidden or obscured in some fashion, and the onus is upon us as designers to be duly diligent and inform ourselves. Perhaps, also, this dimension to material selection should be covered in our curricula for design, materials, and manufacturing courses to help contextualize the impact of our choices and at what cost we specify materials and manufacturing processes. This calls into question how and where materials- and manufacturing-related units/courses have been taught in Industrial Design programs. Often, the teaching of materials is outsourced to other disciplines or taught by engineers or material scientists (Pedgley, 2010), yet materials education needs to not only cover the technical aspects of materials and their associated manufacturing processes, but also the more human facets—the political, social, and cultural dimensions—of materiality.

In one weekend newspaper I discovered many untold stories, simply by making the connections between the headlines, the story of materials, and our complicit consumption of design. In the lifestyle section of the newspaper I see a nice teapot—it appears inspired by the work of one of Christopher Dresser's nineteenth century silverware pieces and I recall something Dresser, one of the founding fathers of Industrial Design, once wrote: "There can be morality or immorality in art, the utterance of truth or of falsehood; and by his art the ornamentalist may exalt or debase a nation" (Dresser, 1859,

p. 17). While Dresser referred to “art” and the “ornamentalist”, today we can replace these terms with “design” and “designer”, and the meaning behind his statement is just as poignant. The question for a designer is whose nation is being debased—perhaps given the globalized context of design and manufacture, it is every nation.

In the process of selecting materials, there is more to design than form and function, economics, environment, and emotion; there are deep-centered human and political dimensions that should also be considered. Labor and human rights along with environmental legislation (or lack thereof) should be factored not only into the selection of materials, but also from where materials are sourced. As consumers and designers, we make material choices. The responsibility and significance of those decisions escalates, however, when we are specifying materials that consumers will inadvertently use—in essence the designer makes the decision to use one material over another on behalf of the consumer.

The intent of the chapter has been to call for a greater awareness of the immaterial dimensions to materials selection, as the designer’s decisions regarding materials can have a significant impact on the human, economic, environmental, political, and cultural fabrics of our global society.

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Interview with

Hella Jongerius

WHAT ARE THE KEY ASPECTS AFFECTING YOUR MATERIAL CHOICES?

It depends very much on the product type — whether it is a single product, a mass-produced consumer product, or so on. But a common point is that the material of a product should have an outstanding performance in its tactility. It should be poetic and help to express the product. The material should also bring a fresh look or a fresh point of view. Sometimes in a piece of furniture, for example, I use an archetypical shape and then I use a material that brings the freshness and a sense of the contemporary. Soft Vase (1994), for example, was very expressive: the shape was an archetype; the material changed the whole thinking of what plastics were. It shows the production processes and it shows the seals, which was not common to plastics. That was also expressing the idea that you don't have to come up with a new shape and function in a product; instead material can be the main player. Skin is the design. Sometimes the product type is so new and strange that it presents a new path. In these cases, I am very conventional in my material choices. I start to whisper; to use materials that people are already familiar with.

In addition, the product should of course be producable. While choosing a material, I am always aware of what is possible to make. I will never come up with an idea for an industrial product with a mentality such as 'let's make it gold'. Such unfounded assertions bring huge costs and prohibit manufacture. So the right material choice at the end comes from the many layers of a puzzle. The outcome brings tactility, form and production together into a poetic whole.

ARE ANY OF THESE ASPECTS DIFFERENT THAN 10-20 YEARS BACK?

I had less experience in materials then. If you are working with industry, which I do now, you have a much larger palette of materials and production systems. If you use the materials and tools in your own workshop, then you are of course limited in a way. Product design in metal can be realized with the involvement of industry and likewise plastics. For textiles, all of the complex constructions come through industrial processes. So my palette has become much wider for both materials and processes. But the criteria of tactility and the poetic approach have always been there. Now I just have different techniques and different materials to make it happen.

BIOGRAPHY

Hella Jongerius (1963) has become known for the special way she fuses industry and craft, high and low tech, tradition and the contemporary.

After graduating Eindhoven Design Academy in 1993 she started her own design company, Jongeriuslab, through which she produces her own projects and projects for clients such as KLM (The Netherlands), Maharam (New York), Royal Tichelaar Makkum (The Netherlands), Vitra (Basel) and IKEA (Sweden).

Her work has been shown at museums and galleries such as the Cooper Hewitt National Design Museum (New York), MoMA (New York), the Design Museum (London), Galerie KREO (Paris) and Moss gallery (New York).

Image Credit: © Jaap Rutten

IF WE SAY 'MATERIALS & SUSTAINABILITY', ...?

In the context of industrial manufacture, it is nowadays a must. I don't have to put it in my agenda — it is already there. I am always aware, for example, that if I choose to use leather, I choose the most sustainable one. And I don't work with big companies that only produce throwaway stuff. This is also a way of being a sustainable designer: to choose companies that are awake and with a sustainable agenda.

WHAT ABOUT 'MATERIALS & TECHNOLOGY' ...?

I am not very attracted to new technologies. Of course you can do laser cuts and 3D prints; but somehow they all look the same — they have the same flavour. They are never surface-oriented. The result never appears 'liquid' in the sense that it does not merge into the product. I am interested in the physical world we have around us, and blowing off the dust of the exciting reality. B-Set (1997) is one of the first industrial products I did. This is the story of imperfection. The form is just an archetype; the material is ceramic. When it is shaped so precisely in industry, it looks like plastics; it is not ceramic anymore, it has lost its tactility. A high temperature oven deforms the ceramic and gives to each bowl a slightly different shape. For this range of industrial objects, and for the world of ceramics, it is a new approach. In Repeat (2002) by making a pattern larger, and repeating that pattern, each time you cut out a piece and apply it onto furniture, you make different furniture, since each textile piece is different than others. It makes you to look from a different angle onto industrial processes.

MATERIALS & USER INTERACTION...?

A material has to reach out to the user. As designers, we do things to make this link between human beings and products. But the challenge is how to build this bridge; how to make this relation happen between an object and a person. At this point comes tactility. As I said before, it is the main subject. It is the main pathway for my designs. I don't have a specific user in mind for tactility: it can be me and myself, or the 'whole world'. I know that I have very normal wishes and can regard myself as a normal consumer. Polder Sofa (2005) is an industrial product. It is very simple: a collage of fabrics, wool, polyester, and cotton to give this huge object an expression and to help consumers make a choice. Material choice, this idea of looking at materials and colors, is the main topic in the sofa. It changes something in the industrial field. All the ingredients come together, they merge; then you have a good product that makes sense.

FROM WHERE DO YOU GET INSPIRATION AND INFORMATION FOR YOUR MATERIAL CHOICES?

Inspiration is everywhere: sitting here, looking around, having a shower in the morning, travelling to the studio, having a conversation on the way, feeling the weather. Because I live, I am alive and I am awake. Everything comes into my personal library in some way. That is the inspiration — being a living person.

HOW DO YOU THINK MATERIALS SHOULD BE TAUGHT IN DESIGN EDUCATION?

In the 1970s as teenagers, we made stuff with our hands in our free times: knitting, making things for our rooms, and so forth. It was a creative period. When I went to the design academy, I knew I had a talent for it: I brought good intuition for materials, colours and textiles. You can learn a lot with education, you become more sensible. But you learn only by doing. A lot of students come as interns to work with us. I know they are very smart and that they know a lot — they are good thinkers. But they have very dumb and inexperienced hands. Through practice, you can learn a lot about materials and design; material intuition comes through such practice.

B-Set

Client: Initiated by the designer / Royal Tichelaar Makkum

Year: 1997

Product Material(s): Porcelain, glaze

Brief Description: By firing the clay at too high a temperature, each element deforms slightly. The imperfect set of tableware is one of the first designs in which individuality is created within serial production, an important theme in Jongerius' work. B-Set was the first porcelain to be produced by Royal Tichelaar Makkum (until 1999 the company had focused only on earthenware and stoneware). B-Set also marks the start of the company's contemporary design collection, and of its close collaboration with Jongerius.

Image Credit: © Royal Tichelaar Makkum

Repeat Dot Print

Client: Maharam, New York

Year: 2002

Product Material(s): Cotton, polyester, rayon, ink

Brief Description: Repeat is the industrial continuation of a theme that started with B-Set (1997): the creation of individuality within serial production. Repeat is an upholstery textile with an unusually long cycle of repetition, introducing random order and the opportunity to create one-offs within a family of furniture items. The pattern refers to silk ties in the archives of the Swiss weaving mill where the fabric is produced.

Image Credit: Repeat Dot Print on All sofa by Francesco Rota for Paola Lenti, Photography by Michael Dreas, courtesy of Maharam

Soft Vase

Client: Initiated by the designer / Droog

Year: 1994

Product Material(s): PU Rubber

Brief Description: The perception of an existing, archetypal vase is changed slightly, due to the application of a soft material where our collective memory expects a hard material.

Image Credit: Robaard/Theuwkens (Styling by Marjo Kranenborg, CMK)

Polder Sofa

Client: Vitra Basel

Year: 2005

Product Material(s): Wood, foams, upholstery of several textiles or leather and several color nuances

Brief Description: Polder Sofa contains a mix of fabrics, colors, industrial elements and craft details. The name and the design refer to the typical Dutch 'polder' landscape: the artificial land reclaimed from the sea by means of long horizontal dykes and intersecting drainage canals. Polder Sofa was Jongerius' first industrially designed piece of furniture and marked the start of an intense collaboration with Vitra.

Image Credit: © Vitra (www.vitra.com)

Interview with

Ece Yalım

WHAT ARE THE KEY ASPECTS AFFECTING YOUR MATERIAL CHOICES?

Our starting point is the *context* and the *story* for a new product. Before taking to paper, before drawing shapes, before thinking seriously about the product, its materials or production. This is so important for us, because if you have a good story behind a design, clients more readily accept what you propose. We also ask the question, 'what can we do different?' Material is one of the aspects we can give answers through. It is not always open though. When working with a manufacturer, we respect their production facilities and methods. But at the same time, we always search for something new regarding materials and introducing a different feeling. We like unexpectedness, as a way to be different in a crowded sector. We like to force the limits, to be original, in both material choices and details of production. In practice we always have a B-plan. For example, if I'm designing a product, one side of me starts with existing accepted materials, and the other side of me says 'why not another material, why not this, why not that, why didn't they ever try this?'. So I go for another direction where I take risks. I always take two directions together.

ARE ANY OF THESE ASPECTS DIFFERENT THAN 10-20 YEARS BACK?

I think the choice of products in front of people is now much wider. End users have learned what's high quality and what's cheap. Before, people didn't really have access to so much product information. So designers are faced with a more knowledgeable public. In the past, 'emotion' — as an aspect of design — was always there to care about, but it wasn't being spoken that much. Today it has become more prominent. Also, today I think designers have more concern about what's going to happen *next*, or what's going to happen *after a while* to the products that they design. They pay more attention to ecological effects. We were a little bit aware with wood, and that trees were being cut too much. That was the first 'material problem'. But twenty years ago, I don't think designers cared about recycled materials at all. Now, everybody is starting to get concerned about that. Even the producers: they care about using materials that can be recycled.

IF WE SAY 'MATERIALS & SUSTAINABILITY', …?

Whatever I design, I prefer it to be timeless. We don't want a product to be used one year and then thrown away the next. Of course there are some sectors where it's not the preferred way, because they want to sell new products. But we try to design in a way that our products will not bore people through time. Boredom is the reason that people start changing products, even though they're still perfectly acceptable and useable. So within this, we choose a material that is really durable — both for function and appearance — that will still be good after ten years. We don't really care too much about fitting to fashions and trends. Tied to this is the

BIOGRAPHY

Ece Yalım received her Bachelor's degree in industrial design from Middle East Technical University, Turkey, in 1988, followed by a Master's degree in interior design from Pratt Institute of Technology, New York, in 1992. In 1996, she founded Artful Interior Design with Oğuz Yalım, where she continues to work today leading interior and product design projects.

Image Credit: © Artful

issue of 'material honesty'. This is really important to me. If you can be honest, as much as possible, that's the best for a designer. But you don't always have a chance to do this, because most of the time you're stuck with a limited range of materials in order to compete with other brands. For me, sustainability should be reached through longevity in the initial design, rather than relying on recyclability. Recyclability is just a word: maybe the recycling facilities don't even exist. I think recyclability makes sense with fast moving products, such as electronics. It's also important not to be wasteful about materials. That's one thing that forces us to decide what to use and what not to use; or, what to use *instead*, because of ecological reasons. For example, we will present the valuable material in a product only in the limited areas where people are exposed to it or where they interact with it. Other materials can be used in places that are not seen or interacted with.

WHAT ABOUT 'MATERIALS & TECHNOLOGY' …?

Most of the time, if companies are using the same production technologies, they end up making use of the same materials. My view is if I don't give anything to clients to improve themselves, I think as a designer I'm not doing anything. If we can add a little bit of something to their production methods — maybe requiring just a small improvement or change — this is good. If we consider innovative materials, we have to be very careful about using the right 'dose'. People have a typical expectation from a product. One technology that really makes a huge difference is finishes. The finish and the overall look have a huge impact on whether people decide to buy a product or not. And it's easy to trick people; it's easy to lead them and dominate them. So within the hands of the designer, finishes command a high level of power, persuasion and responsibility.

MATERIALS & USER INTERACTION…?

User interaction is extremely important; it's the *main thing* about experiencing a product. Most of the time, user interaction is a beginning point for us. Material makes a huge difference. I love touching and feeling and reading products. And I think people really care about it, especially those who care about presenting themselves with their products and, in a way, who show what they want from life, what's their status. Materials then become one of the most important parts; they provide us with a language to express ideas and values. First you see the product materials, and then you start touching. And through touch, we can really start to create that emotional link with a product. It's especially important in today's marketplace. Everybody is coming up with well-designed products that do the job. But which one is going to be the one that you really want to use and hold on to? The one that creates a link to end users. That's why I think interaction and emotions are a lot more important today.

FROM WHERE DO YOU GET INSPIRATION AND INFORMATION FOR YOUR MATERIAL CHOICES?

When you work in the same sector for a long time, such as furniture, it can feel like you always walk to the same point regarding materials. It's a problem of knowing too much about the material you use all the time. So we use inspirational sources to try to get rid of our biases and avoid doing the 'right thing' straight away. We know that we can be inspired by everything: a movie, travel to a new location, sitting in a restaurant and seeing something. In the beginning, maybe we didn't know how to pump our inspiration. But inspiration can be learned: *where* to look, and *how* to look. Our interior design experience inspires us a lot, because it leads us to dream about the space that a product will be placed in, and to consider how they will interact. Without this, a product idea always flies around without any grounding. Probably the main inspiration we get is through observation, being very careful to notice what's happening around us, all the time. Particularly how people behave within spaces. At the same time, we read a lot about how life is going and how things are changing. Art pieces from different materials are also really inspiring. So too are visits to production facilities. We love going in, seeing the material, seeing all these processes being carried out. I also love keeping material samples and products. I always say that every designer has a 'back pack'. You put things into it, even though at the time you don't know when to use them, or how they will be used. But you *know* they will come in useful at some point.

HOW DO YOU THINK MATERIALS SHOULD BE TAUGHT IN DESIGN EDUCATION?

We should guide students to develop critical observation skills. Always, if I see a product, I search for how it is working, how details have been resolved, and I think about the materials that have been used. It can be very revealing and a great source of knowledge. Students have to be observant about these kinds of qualities. Students should also learn how to appraise materials. They should spend more effort looking at materials, touching them, collecting them and seeing how they are applied into products. As students, they don't possess that experience yet. Exposure to good and bad examples of materials use I think can be a great way to learn. Disassembling products, and then reassembling them, emphasizes to students how a product comes together and the effect of material decisions.

Mantar

Client: Paşabahçe Mağazaları

Year: 2009

Product Material(s): Glass with metal electrical accessory

Brief Description: Paşabahçe Mağazaları asked for this lighting product to be suitable for hand-made and glass-blowing techniques but on a larger scale of production. Whilst serving this purpose, Mantar was designed to emphasize the characteristics of handcrafted glass. In particular, care was paid to using different glass colours and types for the separate parts.

Image Credit: © Paşabahçe Mağazaları

Octopus

Client: Artful Collection

Year: 2012

Product Material(s): Beech plywood seat, veneer laminated base

Brief Description: The decision to use laminated wood instead of solid wood was taken to deliberately encourage less use of wood stocks for preservation purposes. Nonetheless, the product still carries the desired warmth of wood to the interiors in which it is placed. A fully painted and lacquered version further reduces the demand placed on sourcing new wood stocks.

Image Credit: © Artful

Scroll

Client: Ersa

Year: 2010

Product Material(s): Wood structure with foam and fabric covering

Brief Description: The small but significant detail of Scroll is an embroidered white line spiralling its way across the pouf surface and running down the pouf sidewall. Suddenly the product is given a playful three-dimensionality that breaks up the otherwise plain material surfaces. Multiple poufs of varied dimensions can be joined to create informal seating spaces.

Image Credit: © Ersa

Join

Client: Ersa

Year: 2010

Product Material(s): Polyurethane seating with metal legs

Brief Description: For waiting rooms and reception areas, it is important to offer comfort and a little sense of being special. The fabric and linear stitching used in Join is intended to bring the plushness of home furnishing to an office context. The seating is configured so as to fit an end-on-end arrangement.

Image Credit: © Ersa

SECTION 2

Living with Materials

In this section, attention is given to the crossovers between materials, design, and sustainability. The contributing authors examine social sustainability, environmental impacts, consumption, waste, product aging, and longevity.

CHAPTER 7

Materials and Social Sustainability

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CONTENTS

MATERIALS, DESIGN, AND SUSTAINABILITY

To meet the basic human needs, natural materials such as wood and stone to build shelters have already been used for thousands of years. Textiles, clothing, and fashion, such as with kimono, have been used as traditional garments worn by men, women, and children, for protection as well as a form of cultural expression. In modern times, our daily life is so much immersed with artefacts made out of diverse materials that even the term "material culture" has been coined in the early twentieth century referring to the intensive relationship between artefacts and social relations, while current discourses about material culture often refer to consumerism and throw-away culture.

Amidst this apparently peaceful material world, a book *The Limits to Growth* (Meadows et al., 1972) appeared some 40 years back showing us by modeling the consequences of unchecked economic and population growth with finite resource supplies. Nevertheless, the concern about the diminishing resources to sustain our material world is of recent origin.

In the mid-1970s, Fred Hirsch explored the other limits. He explored in his book *Social Limits to Growth* (Hirsch, 1977) why the promise of economic growth is reaching an impasse. He argued that the causes of this are essentially social rather than physical. Affluence brings its own problems. As societies become richer, an increasing proportion of the extra goods and services created are not available to everybody. Material affluence does not make for a better society, argued Hirsch. Even in affluent countries, greater income or consumption is not contributing to objective indicators of population health or to subjective

Materials Experience. http://dx.doi.org/10.1016/B978-0-08-099359-1.00007-2

well-being (Siegel, 2006). In fact, a worldwide comparison indicates factors such as social relations, family and friends, societal system, governance, etc. positively influence happiness (Kandachar and Halme, 2008). The current financial crises of the past 5 years in the West have rekindled the interest to inquire whether economic growth can be automatically regarded as a self-evident good, with debates and measures focussed solely on the best means to achieve it. For instance, in a recent book, *How Much is Enough*? (Skidelsky and Skidelsky, 2012), an economist and a philosopher have reminded that society is much more than economic growth alone.

When examined under a global context, a wide range of issues are seen interconnected: climate change, population growth, poverty, urbanization, environmental degradation, biodiversity, conflict, health and well-being, economic turmoil, resource consumption, etc. Global sustainability has become the primary objective of the twenty-first century. At the same time, the paths to arrive at are not straightforward. They are complex and wicked, the remedies are not clear and there is not even a clear consensus on what the problems are. As the concept of sustainability is broadening to align with economic, ecological, as well as social principles, the role of the designer is extending beyond simply designing and developing more environmentally benign products and processes.

Sustainable development, as defined in the United Nations (UN) report *Our Common Future* (Brundtland Commission, WCED, 1987) is the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The least cited portion of this definition is perhaps the first part: (1) concept of "needs", in particular the essential needs of the world's poor, to which overriding priority should be given and (2) idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.

The UN went further and in 1992 Earth Summit placed landmark conventions on climate change and biodiversity, as well as commitments on poverty eradication and social justice. Since then global emissions have risen by 48%, 300 million hectares of forest have been cleared and the population has increased by 1.6 billion people. Despite a reduction in poverty, one in six people are malnourished

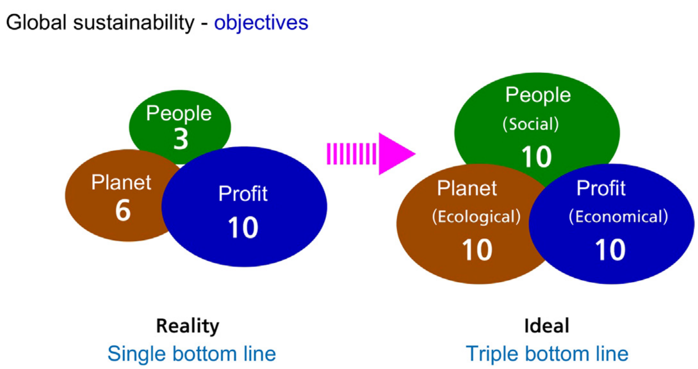

FIGURE 7.1
Need for a balanced attention to all the elements of sustainability. The numbers are author's scorecards. *Kandachar, 2012.*

(Watts and Ford, 2012). Of the three pillars of sustainability, social, environmental, and economic, social sustainability (and socially responsible design) is the least addressed (Figure 7.1), although the Brundtland Commission emphasized the strong linkage between poverty alleviation, environmental improvement, and social equitability through sustainable economic growth.

Currently, our world is facing many challenges to strive for global sustainability. Many parts of the world are going through a period of rapid economic growth and entering a transitional phase between developing and developed status, although the gap between wealthy and poor has kept widening (Kandachar and Halme, 2008). This growth would also mean, if the traditional developmental models continue to be followed, an increasing, and increasingly affluent global population results in an increased consumption. McKinsey estimates that by 2025, the annual consumption of all products together will reach $30 trillion in emerging markets, almost the same as the richer part of the world (McKinsey, 2012). There is a difference, however. Today, inhabitants of industrialized countries use 4–8 times more resources than people living in agricultural societies and 15–30 times more resources than people in hunter-gatherer societies (SERI, 2009). This would result in an enormous increase in environmental impacts in the nearby future as well as a rapid depletion of material resources.

The resources being finite on this planet, the need to address the link between population growth, economic growth and affluence, resource use, and the enlarging ecological footprint in our societies is becoming urgent. The current model of economic growth depends on high and growing levels of continuous consumption. Urgent and fundamental questioning of the current models of economic development followed by adequate policy measures are needed both in developed and in developing countries (Kandachar, 2012).

To continue to provide a high quality of life for a predicted 9 billion people on our planet, without exhausting the Earth's resources or irreparably damaging its natural systems, global solutions for sustainable consumption and production are needed. These require practical steps that are urgently

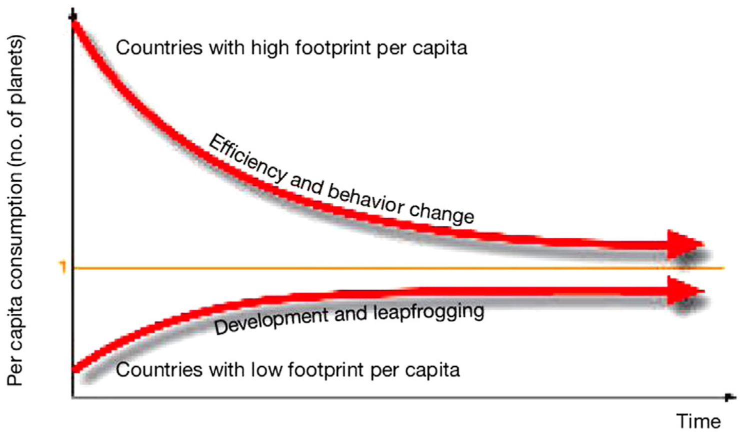

FIGURE 7.2
Challenges and opportunities from a global perspective. *Tunçer, 2008.*

needed to realize drastic reduction of consumption as well as a behavioral change directed toward appropriate lifestyle in the richer part of our world (Figure 7.2).

Design of products and services (and systems) is a key contributor to realize these objectives. Designing with materials requires radical reduction in their use. In addition, innovations with local materials, if properly engineered to improve quality of life, should be able to lead to social sustainability of millions of poor all over the world.

MATERIALS RESOURCES AND SOCIAL SUSTAINABILITY

What is social sustainability? While the three dimensions of sustainability—environmental, economic, and social—are interdependent, it is particularly difficult to define, realize, and operationalize social sustainability (Boström, 2012). According to Bebbington and Dillard (2009), the reasons for this difficulty are "*Social sustainability appears to present different and more severe challenges … than environmental sustainability because there is no widely accepted scientific basis for analysis, unlike the ability to debate population ecology, acceptable levels of toxicity, or acceptable concentrations of green-house gases in the atmosphere. Nor is there a common unit of measure such as monetary units with the economic dimension of sustainability*". However, recently an attempt has been made to visualize what social sustainability often refers to both in terms of the improvement of conditions for living people and future generations and in terms of the quality of governance of the development process. This study (Boström, 2012) has published examples of substantive (what) and procedural (how) aspects of social sustainability. They include

1. *Substantive aspects: what social sustainability goals to achieve?*
   (a) Basic needs such as food, housing, and income and extended needs such as recreation, self-fulfillment; (b) employment and other work-related issues, facilitating for local small and medium enterprises; (c) security (e.g., economic and environmental); (d) health effects among workers, consumers, and communities; and (e) quality of life, happiness, and well-being.
2. *Procedural aspects: how to achieve sustainable development?*
   (a) Proactive stakeholder communication and consultation throughout the process; (b) empowerment for taking part in the process (e.g., awareness, education, and economic compensation); (c) participating in the framing of issues, including defining criteria, scope, and subjects of justice; (d) social monitoring of the policy, planning, and standard-setting process; and (e) accountable governance and management of the policy, planning, and standard-setting process.

The table in this study is much larger than the one shown here. Even in this limited section, it can be seen that it is difficult to assign quantitative and measurable criteria for these factors. 1(b) perhaps is the one parameter that is reasonably measurable, although specific and accurate data on the number of agricultural producers involved in producing say, natural fibers, in different parts of the world is hard to get.

Three types of reserves of natural resources have been identified (Chapman and Roberts, 1983): (1) continuous resources such as sunlight and wind, the use of which does not lead to a reduction in their size; (2) renewable resources, such as wood and crops that can be replenished by harvesting—but not faster than their rate of replenishment; and (3) nonrenewable resources such as fossil fuels and minerals, which are extremely slowly replenished. Other nonrenewable resources include clean water, fertile soils, biodiversity, etc.

Abundant availability of natural resources does not automatically lead to economic growth (Barbier, 2003). In fact, in modern times, economies with abundant natural resources have tended to grow less rapidly than natural-resource-scarce economies (Sachs and Andrew, 1999). In addition, almost all over the world the essence of economic development appears to be an approach toward adding value, by designing and producing goods with ever higher value per kilogram. Table 7.1 illustrates the effect of value addition to especially nonrenewable natural resources.

Current emerging global economy is demonstrating that the wealth and prosperity of a country depends largely on its technological capacity to add value to the natural resources the country possesses. Competences in product design confer the ability to transform the natural resources into products that are marketable both in domestic and in international markets.

At the same time, although industrialized countries have focused on substitutability, permitting them to do without a particular material, there is a limit for this strategy with upcoming materials scarcity, while the manufacturing and service sectors are critically dependent on raw materials inputs (Radetzki, 2010).

Plant crops, the main products of agriculture, are an essential source of food, feed, raw materials, energy, etc. This chapter focuses on a limited set within the large domain of agricultural raw materials, namely, on natural fibers, such as jute, kenaf, flax, sisal, abaca, and coir. It demonstrates what the role of design can be by exploring the possible use of these materials in design and development of consumer and/or industrial products so as to improve the quality of life of producers of these materials.

Table 7.1 Value in US$ per kg, at Prices in 2000

Material	Value	Product	Value
Iron ore	0.02	Newsprint	0.40
Steam coal	0.03	Super tanker	2.00
Wheat	0.12	Motor car	15.00
Crude oil	0.21	Dish washer	25.00
Standard steel	0.25	TV set	60.00
		Submarine	100.00
		Large passenger aircraft	600.00
		Laptop computer	1000.00
		Mobile telephone	2000.00

Radetzki, 2001.

NATURAL FIBERS

In December 2004, the UN Food and Agriculture Organization (FAO) Intergovernmental Group on Hard Fibres and on Jute, Kenaf and Allied Fibres, thought of calling for a United Nations International Year dedicated to natural fibers. The purpose was to focus world attention on the role that natural fibers play in contributing to food security and poverty alleviation. After extensive preparations by the FAO, the UN General Assembly declared 2009 as the International Year of Natural Fibres (IYNF, 2009).

The International Steering Committee set up in 2005 to guide the activities of the IYNF, adopted a definition of natural fibers as "those renewable natural fibres of plant or animal origin which can be easily transformed into a yarn for textiles". This definition, by limiting to "yarn for textiles", does not do justice to the enormous diversity of products natural fibers can produce, like, in addition to textiles for clothing, strings, ropes, paper, and to strengthen building materials, etc.

Natural fibers are produced from animals or plants. Examples of animal fibers are wool and silk. Plant fibers are derived from the stem, leaf, or seed of various plants. They include bamboo, banana, coconut, cotton, flax, grasses, hemp, jute, kenaf, maize, mohair, pineapple, rice, sisal, soya, sunflower, and wood. The oldest building materials are natural: wood, bamboo, silk, eggshells, etc. They are by nature highly optimized for the functional requirements (e.g., trunks, branches, legs, and wings to support or propel the organism), or they are highly stressed structural members (wood and bone) and are capable of adapting to change during living (bone, wood every year), modifying properties to the requirements (Kandachar and Brouwer, 2002).

The fibers themselves are cellulose fiber-reinforced materials as they consist of microfibrils in an amorphous matrix of hemicellulose and lignin, the microfibrils being very rigid and quite stable imparting high tensile strength. The matrix is responsible for most of the physical and chemical properties such as biodegradability, flammability, sensitivity toward moisture, thermoplasticity, degradability by ultraviolet light, etc. This composition is also responsible for good heat, sound and electrical insulating properties, high coefficient of friction (antislip properties), and combustibility (allowing disposal by incineration) yet meeting flammability requirements of automotive industry. Bast fibers (especially flax fibers) have bad odor.

Current processes of harvesting also result in a woody content (shive), which is sometimes not acceptable in the appearance of molded parts. Shive is the lignified inner tissue of the stem and is the by-product of fiber production. Flax fiber, for instance, constitutes about 25–30% of the stem resulting in large quantities of shive. Shive, however, being a lingocellulosic by-product, can be pyrolyzed and activated to produce activated carbon. Even otherwise, shive has applications such as chip board, animal bedding, and burning for thermal energy (Marshall et al., 2007).

Value addition by converting fibers to products is also a common practice. Jute, for instance, is a natural fiber, grown in a crop rotation system with rice/vegetables, providing the farmers with a profitable crop all year round. Jute is biodegradable. All parts of the jute plant are useful: leaves for food, husk for firewood, and the pith to make the fiber. Jute bags are reusable, with a life of approximately 3–4 years. Jute bags have one of the lowest carbon footprints of all available reusable bags, largely due to the manual processes involved in their production. Jute scores equally well in water footprint. Jute has one of the lowest water footprints of any materials used in reusable bags as it needs low quantity of fertilizers and does not rely on irrigation.

Nearly all growth in the world population of about 2.3 billion people, between 2009 and 2050, is forecast to take place in the developing countries. Large numbers of people living in these countries are dependent on agriculture, while they also cherish an improved quality of life. For instance, agriculture plays an important role in Pakistan's economy, contributing 21% to gross domestic product and employing 44% of the total workforce (PIDE, 2012). About two-thirds of the total population of the country reside in rural areas and directly or indirectly depend on agriculture for their livelihood. The sector provides raw materials to the industrial sector and is an important source of demand for its products (Table 7.2). The livelihood of about two-thirds of the country's population that resides in rural areas directly or indirectly depends on agriculture and allied activities.

Table 7.2 Estimated Global Production Volume Averages of Different Natural Fibers (in Million Tons per Year Average Over the Recent Years) and Their Main Products

Fiber	Annual Production, Million Tons	Main Producer Countries	Main Products
Cotton	25.00	China, United States, India, Pakistan	Apparel (60%), furnishing, nonwovens, specialty paper, cellulose, medical and hygienic supplies
Kapok	0.03	Indonesia	Pillow, mattress
Jute	2.50	India, Bangladesh	Hessian, sacking
Kenaf	0.45	China, India, Thailand	Carpet backing
Flax	0.50	China, France, Belgium, Belarus, Ukraine	Textile fabric, composites, nonwoven, insulation mats
Hemp	0.10	China	Specialist paper
Ramie	0.15	China	Textile fabric
Abaca	0.10	Philippines, Equador	Specialty paper, tea bags
Sisal	0.30	Brazil, China, Tanzania, Kenya	Twine and ropes
Henequen	0.03	Mexico	Twine and ropes
Coir	0.45	India, Sri Lanka	Twine, ropes, carpets, brushes, mattress, geotextiles, horticultural products
Wool	2.20	Australia, China, New Zealand	Knitted wear
Silk	0.10	China, India	Fine garments, veils, and handkerchiefs
Man-made cellulosic fibers	3.30		

Van Dam, 2008.

Growth and utilization of natural fibers is a socially responsible venture, supporting livelihoods of millions of small-scale farmers and low-income workers (IYNF, 2009; Jutexpo, 2012; Tambyrajah, 2012).

The jute industry in India, for instance, the biggest in the world, provides direct employment to about 0.26 million workers and supports the livelihood of around 4 million farm families. Bangladesh in 2008 produced 931,000 tons of jute, involving 750,000 farmers, 145 jute mills, and a total work force of 2.5 million.

The sisal sector in Brazil provides direct and indirect employment to some 850,000 people, with about 35,000 farmers active in sisal cultivation, serviced by some 3000 mobile fiber extraction units operating from farm to farm. About 100 businesses are involved in preprocessing of sisal fiber and 14 businesses producing finished products such as carpets, yarns, etc. Tanzania also produces large quantities of sisal. Sisal cultivation and processing in Tanzania directly employs 120,000 people and the sisal industry benefits an estimated 2.1 million people. There are more than 20,000 fiber cultivation units and about 3000 fiber extraction units in Tanzania. About 280 companies account for the production of semi-finished products and trading activities.

Coir fiber from coconuts is produced in India, Sri Lanka, Philippines, and Vietnam. The coir sector in India alone employs some 700,000 persons, mainly women, operating from some 10,000 production units. In Sri Lanka, there are some 200 registered coir mills in operation, with most of them being single ownership with coir fiber as the main source of income. Most of the mills employ between 10 and 30 people (men and women).

Most of the world's abaca production is from Philippines where it is estimated that more than 114,000 farmers/fiber extraction units and 680 semifinished production and fiber trading companies are in business.

More than 60% of the world's cotton is grown in China, India, and Pakistan, where it is cultivated mainly by small farmers and its sale provides the primary source of income of some 100 million rural households. An estimated 1.5–2 million small farms in West and Central Africa grow cotton with about 10 million people employed in the region's cotton sector. Raw cotton with about 50% of exports is vital to the economies of Benin, Burkina Faso, Chad, Mali, and Togo. Cotton is Mozambique's second most important export, is grown by some 300,000 rural families, and provides work for 20,000 people along the supply chain.

DESIGN AND DEVELOPMENT

Development as we see in the Western capitalist world-system involves producers and traders and the driving force (Southwell, 2000) is global accumulation of wealth. Designing of products transforms and adds value in such a system to support wealth accumulation mainly by the producers and traders. Many designs in developing countries fall under the term "craft", involve local materials and technologies, design process based on intuitive methods, and are often a result of participation and empowerment. The West has undergone a change from the craft work of preindustrial design to the mechanization of industrial design. This has also resulted in the development of "scientific design" based on scientific knowledge but utilizing a mix of both intuitive and nonintuitive design methods, reflecting the reality of modern day design practice (Cross, 2001).

Even though they are not formally trained, the poor in developing countries have often demonstrated that they—either individually or community led—are capable of innovating too, resulting in "grassroots innovations" or "local innovations". This is a result of developing products by the farmers (or other users), for instance, to meet their own needs, without external support, by making use of local resources, addressing specific constraints, challenges, or opportunities perceived at a local level (Letty and Waters-Bayer, 2010).

Developing countries have extensive experience in craft work too. Some of them are slowly realizing the importance of industrial design as a strategic tool for economic growth, and giving this an important status equal to other fields such as science, technology, and economics. Examples include countries such as Malaysia (Malaysia Design Council, founded in 1993), Indonesia (Indonesian Design Center, founded in 1995), Philippines (Product Development and Design Center of the Philippines), Thailand (Office of Product Development & Design for Export), India (National Institute of Design, founded in 1969), Colombia (Artesanías de Colombia), Cuba (Oficina Nacional de Diseño Industrial—National Office of Industrial Design), Mexico (Mexico Design Promotion Center), Brazil (Brazilian Design Center), and South Africa (SABS Design Institute). Although these initiatives are laudable, such initiatives appear to be directed to meet the competitiveness in the international market, rather than addressing the needs of their own country in terms of alleviating poverty as well as fulfilling the basic needs of the local people. A national design policy followed by appropriate measures, therefore, directed to meet the social and economic challenges of the developing countries aimed at the betterment of their own society seems to be more than relevant and needed.

During the first part of the last century, petrochemical industry and synthetic materials based on this industrial sector have made considerable scientific and technical progress to enable mass production of qualitatively superior products. This is not unnoticed by the natural fibers sector. Natural fibers are being displaced by synthetic, man-made materials such as polyester, acrylic, and nylon. These materials are much cheaper and easier to manufacture in bulk, and easily create uniform colors, lengths, and strengths of materials that can be adjusted according to specific requirements. Synthetic materials like fibers and plastics with their products like synthetic fabrics and acrylic carpets have successfully taken over the markets, which were till then a domain of natural fibers and materials. In just over 15 years (1939–1954), the percentage of American women who preferred silk hosiery dropped down from 93% to 0.2%, while nylon went up from around 5% to 98.7% (Lemelson Center, 1998). The major driving forces of such development till recently have been technical as well as economic benefits. The production of synthetic materials, however, is a strong contributor to carbon emissions and waste. According to the United Nations Industrial Development Organization, it is estimated that every person in the world is responsible for 19.8 tons of carbon dioxide emissions in their lifetime, simply because the clothes include synthetic fibers (Stone, 2010).

Lightweight designs are capable of contributing toward sustainable development by minimizing material usage and cost. Materials of renewable resources on their own can contribute toward

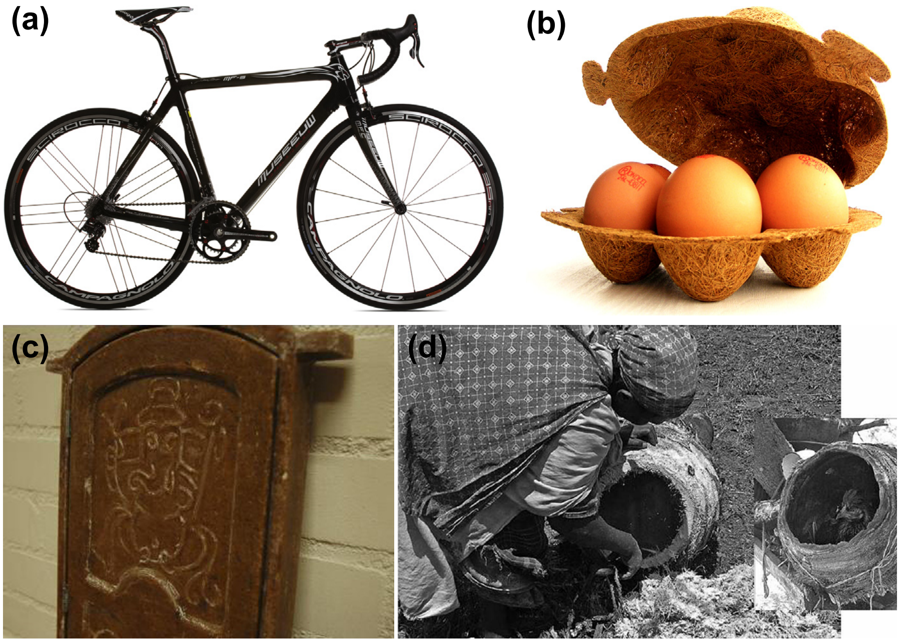

FIGURE 7.3

(a) Museeuw racing bike from Belgium, with frame in flax and carbon fibers *(Source: naturalfibres2009.org)*. (b) Egg packaging in natural coconut fiber and natural rubber *(Source: John van den Hout, ENKEV BV, The Netherlands)*. (c) Prototype of a door and door frame in flax fiber-reinforced polyester *(Source: Boekhoven, 2005)*. (d) Chicken nesting boxes made out of sisal stems. Local innovation at Mpumalanga, South Africa. *(Source: Letty and Waters-Bayer, 2010).*

sustainable development too, if they are exploited in such a way that the rate of use does not exceed the rate of renewal. These natural materials are being rediscovered for applications in product design. Agricultural fibers, like flax, hemp, sisal, etc., are currently receiving considerable interest in the field of industrial applications, as a source of reinforcement to manufacture polymer composites. This interest is partly due to the environmental concern about synthetic fiber composites. Second, they have a potential in cost and weight reduction. They can be used as reinforcing fibers instead of glass fibers in composite materials. They have a high specific stiffness (e.g., flax has a stiffness comparable to glass at half the density) and natural fiber composites have nonbrittle fracture behavior, which is an advantage in automotive interiors. Finally, from the view of occupational (during assembly and handling) health and safety, natural fibers are preferred to glass fibers. Natural fibers are less abrasive for tooling while glass in the form of airborne particles can cause respiratory problems. During the last decade, the automotive sector, especially in Germany, has responded with considerable interest in these materials. Automotive brands such as Volkswagen, Audi, BMW, Daimler Chrysler, Opel, Peugeot, Renault, and Mercedes Benz trucks have components made of natural fiber composites (Ton-That and Denault, 2007).

Technical constraints for widespread use of natural fibers in an industrialized setting include the limited consistency in the quality of fibers, their thermal stability and their ability to absorb moisture, and limited impact strength when used as composites. In addition, lack of availability of extensive property data, comparable to those on synthetic fiber composites, is an important contributing factor (Kandachar, 2002). Production in an industrial setting brings its own limitations such as problems of stocking natural fibers for extended time with a possible consequence of degradation and biological attack of fungi and mildew.

Some examples of applications of natural fibers in product design include (1) products designed in the West, especially for the Western market, Figure 7.3(a) and (b); (2) products designed by a Western designer to meet the social needs in a developing country, Figure 7.3(c), and (3) local innovations by local people, Figure 7.3(d).

CONCLUSIONS

Social sustainability is the neglected component of sustainability. Our world during the last decades has focused, however, only on economic sustainability. Although this approach has delivered extensive material welfare to some parts of the world, a large part of the world is still struggling to make a decent living. Even in the richer parts of the world, the current financial crises are fueling inquiries whether economic growth can be automatically regarded as a self-evident good. Meanwhile, as a result of population explosion and concomitant increase in affluence, including in some developing countries, the ecological footprint is expected to drastically rise accompanied by resource strain. This calls for worldwide measures. Some developing countries are investing in mastering of industrial design competences. In addition, they possess and have the capacity to grow natural and renewable resources such as natural fibers. These raw materials have the potential to contribute toward the social sustainability of people living in these countries. These fibers are already providing livelihood for millions of farmers. By appropriate policy measures coupled with "scientific design" approaches, industrial designers can contribute to the quality of life of millions of poor by designs appropriate to the local context.

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CHAPTER 8

The "Material" Side of Design for Sustainability

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CONTENTS

Historically, since the emersion of environmental issues, the focus has moved from end-of-pipe action and research to research and innovation efforts that aim to diminish unsustainable systems of production and consumption. In this framework, it is possible to trace briefly some fundamental levels in the ongoing interpretation of sustainability by the design world.

In fact, the discipline of design for sustainability (DfS) has enlarged its scope and field of action over time, as observed by various authors (Bhamra and Lofthouse, 2007; Karlsson and Luttrop, 2006; Rocchi, 2005; Santos dos, 2008; Vezzoli and Manzini, 2007).

In the industrialized contexts, a first level on which numerous theorists and academics have been working is the *selection of resources with low environmental impact: materials* in one direction and *energy sources* in the other.

Since the second half of the 1990s, attention has somewhat shifted to the product level, to the design of products with low environmental impact, usually referred to as *product Life Cycle Design* (LCD), *Ecodesign*, or *product Design for Environmental Sustainability* (Alting, 1993; Benjamin et al., 1994; Brezet

Materials Experience. http://dx.doi.org/10.1016/B978-0-08-099359-1.00008-4

and van Hemel, 1997; Crul and Diehl, 2009; European Union, 2005; Giudice et al., 2006; Haushild et al., 1999; Heiskanen, 2002; Hemel, 2001; Hemel van, 1998; Keoleian and Menerey, 1993; Manzini and Vezzoli, 1998; Sun et al., 2003; Vezzoli and Sciama, 2006). In those years, two main concepts were introduced. First, the concept of *life cycle thinking*: from product design to the design of product life cycle stages, i.e., all the activities needed to produce the materials and then the product, to distribute it, to use it, and finally to dispose of it, are considered as a single unit. Second, the concept of *functional thinking* from an environmental point of view, i.e., design and evaluate a product's environmental sustainability, beginning from its function rather than from the physical product itself.

Since the end of the 1990s, starting with a more stringent interpretation of sustainability—that tells us we must work radical changes in production and consumption models—attention has partially moved to *design for the ecoefficient Product-Service System (PSS)*, therefore to a wider dimension than that of the single product (Bijma et al., 2001; Brezet, 2001; Charter and Tischner, 2001; Cooper and Sian, 2000; Goedkoop et al., 1999; Hockerts, 1998; Lindhqvist, 2000; Manzini and Vezzoli, 2001; Stahel, 1997; Tischner and Vezzoli, 2009; UNEP, 2002; Van Halen et al., 2005; Vezzoli, 2010; Zaring, 2001). Among the several converging definitions, the one given by the LeNS EU funded project* (Vezzoli et al., unpublished data) says that an ecoefficient PSS is "an offer model providing the integrated mix of products and services that are together able to fulfill a particular customer demand (to deliver a 'unit of satisfaction') based on innovative interactions between the stakeholders of the value production system (satisfaction system), where the economic and competitive interest of the providers continuously seeks environmentally beneficial new solutions. In this context, it has even been argued (Vezzoli, 2003a) that the design conceptualization process needs to shift from *functional thinking* to *satisfactional thinking*, in order to emphasize and to be more coherent with the enlargement of the design scope from a single product to a wider system fulfilling a given demand of needs and desires, i.e., a *unit of satisfaction*.

Still more recently, design research has opened discussion on a possible role of *design for social equity and cohesion* (Crul and Diehl, 2006; EMUDE, 2006; Kandachar, 2010; Leong, 2006; Mance, 2003; Margolin, 2002; Penin, 2006; Razeto, 2002; Rocchi, 2005; Tischner and Verkuijl, 2006; Vezzoli, 2003b; Vezzoli, 2010; Weidema, 2006). Hence, a potential role for a design directly addressing various aspects of social inequality, aiming at a "just society with respect for fundamental rights and cultural diversity that creates equal opportunities and combats discrimination in all its forms" (EU, 2006). Most of the authors (Crul and Diehl, 2006; Kandachar, 2010; Santos dos et al., 2009) work on the role of design in serving people's basic needs, i.e., design for the base of the pyramid. The author of this chapter proposed the working hypothesis of a more systemic design approach, i.e., PSS design for low-income and emerging contexts (Vezzoli, 2010).

When speaking about material selection and DfS, it is necessary to have in mind the overall picture described above; otherwise, we may encounter the risk of believing DfS is just a matter of material selection. Namely, without an introduction to the product LCD approach, as clarified above, it could result in misleading any arguments about low environmental impact material selection in product

*LeNS, the Learning Network on Sustainability, is a project funded by the Asia-Link Programme, EuropeAid, and the European Commission, for curricula development and teaching diffusion in worldwide design higher education institutions, on design for sustainability focused on Product-Service System innovation.

design processes: this is given in the following chapter. Within this framework, the following DfS strategies related to materials selection are described thereafter: minimize material consumption, select nontoxic and harmless materials, select renewable and biocompatible materials, and extend the lifespan of materials (recycling, composting energy recovery). Finally, some conclusions are drawn clarifying the importance of material selection, by framing it into a system approach to DfS, encompassing environmental, economical, and socioethical.

INTRODUCTION TO THE PRODUCT LCD APPROACH

In this chapter, we will briefly bring up the main notions of product LCD. First, we define the *environmental requirements*, then introduce the notions of *life cycle approach* and *functional unit*, *life cycle assessment* (LCA), and finally the *LCD strategies.*

(Design) Environmental requirements

As in design processes, we might have performance requirements, ergonomic requirements, cost requirements, etc. When the concern is on the environmental requirements, these are related to environmental damaging effects, such us global warming (greenhouse effect), ozone layer depletion, eutrophication, acidification, smog, toxic emissions, and waste being the main. Without going any deeper into details, it is important to keep in mind that design (should) aims to reduce the influence of products on these effects, and thus the real issue lies in the capability to associate the above-mentioned effects to a product. For example, can we relate a calculated amount of global warming to a given product, e.g., a television being used in a certain way? The answer is yes, thanks to two concepts:

- the product life cycle and
- the functional unit.

In the following paragraphs, these two concepts are clarified. Thereafter, the most consolidated method to assess the environmental impact of a product (using the above two concepts) is introduced, i.e., LCA.

The product life cycle phases

Assuming a *product life cycle* approach means to consider any effects with the *biosphere* and *geosphere* determined by all the inputs and outputs of all the processes associated with a given product. Usually five life cycle phases are identified (although all the processes related to all the *life cycle* phases are considered simultaneously as a single unit):

- **preproduction**, encompasses the raw material/resources/supplies acquisition, and refinement processes;
- **production**, the processing, assembling, and finishing phases;
- **distribution**, packing, transport, and storage;
- **use** of the product, including consumption of the resources required for its operation, if applicable, and connected processes like maintenance;
- **disposal** of the product, which may follow a number of different paths after its re-collection: landfill, incinerator, conversion into compost, recycling, *remanufacturing*, or reuse (of the entire product or some of its parts).

The functional unit

The second key notion is the *functional* approach. The environmental assessment, and therefore also design, must have as its reference the function provided by a given product, the so-called *functional unit*. So forth the design must consider the product less than the function procured by the same product, e.g., to consider different transportation methods (car, bus, airplane, etc.) as each fulfilling a need to move a given number of persons for a given distance. The comparison between a car and a bus in their life cycle phases could be a helpful example here. If we compare the life cycles of these two products, even without complex calculations, it appears evident that the bus has greater impact in every phase, i.e., a car is made up of fewer materials to be preproduced, produced, distributed, and disposed, as well as consuming and emitting a lower amount per kilometer traveled. Nevertheless, when considered according to their functional unit (in this case, the transportation of 1 person per kilometer) assuming that one car carries on average 2 persons while the bus carries 20, it appears that we should have had compared the bus with 10 cars instead; hence, the environmental impact of the car could be easily guessed as greater than that of the bus. In other words, it is not just the mere product to be assessed (and designed), but all processes associated with the fulfillment of a given function.

Life Cycle Assessment

Among other developed methods, the most reliable for making environmental assessments of a product's life cycle is called life cycle assessment.

The International Organization for Standardization (ISO 14040, 1997) defines LCA as "Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle".

LCA consists of four distinct phases:

- Goal and scope definition (study model that defines the methodological framework that all other LCA phases must comply with).
- Inventory of all the inputs and outputs related to the product system.
- Assessment of the potential impacts associated with these inputs and outputs.
- Interpretation of the inventory data and impact assessment results related to the goal and scope of the study.

LCA has become an important tool for the environmental impact assessment of products and materials and businesses are increasingly relying on it for their decision making. The information obtained from an LCA can also influence environmental policies and regulations, and orientate design processes.

Product LCD strategies

The discipline integrating environmental requirements within the design process is called product *Life Cycle Design*, LCD[1]. The environmental aim of LCD is to reduce the input of materials and energy, as

[1]Among other similar terms, the most common are Ecodesign and Design For Environment. They all indicate a designing approach that aims at reducing environmental impact. However, Life Cycle Design expresses the basic criterion more forcefully: the reduction of environmental impact throughout the entire life cycle.

well as the impact of all emissions and waste, both quantitatively and qualitatively, which also means to assess the harm done (e.g., with LCA, as just introduced) by the processes at every stage of a product's life cycle (in relation to a given *functional unit*).

The presupposition of a life cycle development approach attempts to intervene upstream in order to prevent dangerous emissions and reduce consumption of resources. It is more effective (and *cheaper*) to prevent harm to the environment at the design stage than to try to remedy things once the product is on the market. The importance of an LCD approach is therefore to identify and bring together environmental advantages with economic and competitive ones.

In summary, there are two key approaches introduced by an LCD approach as described.

- First, to adopt an extended design horizon moving from product design to the design of the *product life cycle stages.*
- Second, the design *reference* (what we are designing), which has moved to designing the product's *function* before the product itself.

When approaching LCD, it is useful to bear in mind the following strategies that can direct product development toward reduced environmental impact (from Vezzoli and Manzini (2007, 2008)):

- **minimize resource consumption**, i.e., design aimed at reducing the usage of materials and energy of a given product in the overall life cycle stages or, more precisely, of a given functional unit offered by that type of product;
- **selecting nontoxic and harmful resources**, i.e., design aimed at selecting nontoxic and harmful materials and energy sources in the overall life cycle stages;
- **selecting renewable/biocompatible resources**, i.e., design aimed at selecting renewable/ biocompatible materials and energy sources;
- **optimizing the lifespan of products**, i.e., design aimed at extending product (and component) life span and/or at intensifying product (and component) use;
- **improve lifespan of materials**, i.e., design aimed at valorizing material from scrapped products, so rather than ending up in landfills, they can be reprocessed to obtain new secondary raw materials (recycled or composted), or incinerated to recover their energy content (when applicable);
- **design for disassembly**, i.e., design aimed at easy separation of parts (for maintenance, repairs, updating, or reuse) or incompatible materials (waiting to be recycled or incinerated for energy recovery). This strategy is therefore helpful in *optimizing the lifespan of products* and *improving the lifespan of materials*.

MATERIAL SELECTION IN A PRODUCT LCD APPROACH

Material selection aimed at causing the lowest environmental impact needs to be seen in a systemic approach, i.e., it is mandatory to refer to the life cycle of the product and to its functional unit. In other words, the selection of low environmental impact materials has to be seen through the product LCD approach. Furthermore, in the context of a business model, in which it is the economic and competitive interest of the providers that continuously seek environmentally beneficial new solutions, the LCD approach should be framed within a wider PSS approach.

From this perspective, the following chapter presents some design strategies and guidelines related to selecting materials with a low environmental impact, as related to the product LCD approach and strategies. In particular, we will see the following strategies:

- **minimize material consumption;**
- **select nontoxic and harmless materials;**
- **select renewable and biocompatible materials;**
- **improve lifespan of materials (including design for disassembly).**

Minimize material consumption

Minimize material consumption denotes design aimed at reducing the usage of materials of a given product or, more precisely, of a given functional unit offered by that type of product, i.e., it is a *quantitative* impact reduction. Materials, albeit with different intensity for different products, are used throughout the entire life cycle. For that reason, the design approach must aim at reducing consumption of materials at all stages. It is obvious that a reduction in the use of materials determines cancellation of environmental impact regarding what is no longer used. Using less material diminishes impact, not just because fewer materials are preproduced, but also due to avoiding their transformation, transport, and disposal.

Table 8.1 contains guidelines to *minimize material consumption*, as defined and adopted by the *Design and Innovation for Sustainability (DIS)* research unit[2] of the INDACO Department of Politecnico di Milano.

Selecting low environmental impact materials

Selecting low environmental impact materials implies design activity that selects materials with the highest environmental quality, i.e., it is a *qualitative* impact reduction.

Relating to this, it is important to remember that a properly effective approach must always refer to the entire life cycle (to every concurring process) and to the functional unit. In other words, various processes for producing the materials (some of them might entail toxic or harmful emissions, others equally effective might not) have to be considered along with the technologies transforming and treating materials, as well as the distribution systems and the end-of-life treatments applicable to any given material.

Altogether, in a situation that aims at safeguarding resources for future generations, it is highly important to make choices oriented to their renewability: materials deriving from resources that are less exposed to exhaustion should be preferred.

Finally, in pursuit of clarity, selection of low-impact materials can be divided into

- *Select nontoxic and harmless materials.*
- *Select renewable and biocompatible materials.*

[2]The author is the head of the DIS research unit.

Table 8.1 Guidelines to Minimize Material Consumption

Minimize Material Consumption
Minimize material content
• *Dematerialize* the product or some of its components • *Digitalize* the product or some of its components • Miniaturize • Avoid oversized dimensions • Reduce thickness • Apply ribbed structures to increase structural stiffness • Avoid extra components with little functionality
Minimize scraps and discards
• Select processes that reduce scraps and discarded materials during production • Engage simulation systems to optimize transformation processes
Minimize or avoid packaging
• Avoid packaging • Apply materials only where absolutely necessary • Design the package to be part (or to become a part) of the product
Engage more consumption-efficient systems
• Design for more efficient consumption of operational materials • Design for more efficient supply of raw materials • Design for more efficient use of maintenance materials • Design systems for consumption of passive materials • Design for cascading recycling systems • Facilitate the user to reduce materials consumption • Set the product's default state at minimal materials consumption
Engage systems of flexible materials consumption
• Engage digital support systems with dynamic configuration • Design dynamic materials consumption for different operational stages • Engage sensors to adjust materials consumption according to differentiated operational stages • Reduce resource consumption in the product's default state
Minimize materials consumption during the product development phase
• Minimize the consumption of stationery goods and their packages • Engage digital tools in designing, modeling, and prototype creation • Engage digital tools for documentation, communication, and presentation.

From Vezzoli and Manzini (2007, 2008).

Select nontoxic and harmless materials

To illustrate the environmental impacts of materials, we have to understand that, except for toxic materials (such as asbestos—which should be avoided anyway), the environmental impact depends upon both

- the *material-specific characteristics* and
- the *product-specific characteristics* a material can bestow (to a product).

Let us take as an example a composite material comprising a polymeric matrix filled with fibers. Although it is used to manufacture disposable dishes, it is a very *bad* material with regard to environmental impact, since it causes many problems in the disposal phase and it is very resource-intensive during production.

On the other side, the same composite material could be *good* (i.e., possess a low environmental impact) if used to produce some parts of a product that will be moved during its use (e.g., a car); in fact while this material is probably lighter than others, it will, by reducing the overall weight, reduce the whole fuel consumption in transportation. Therefore, in consideration of products for which the greater environmental impact is in the usage phase (due to fuel consumption and related emissions), the material might be regarded as *good* in environmental terms (i.e., by making the same product lighter and so forth, reducing the consumption and emission per kilometer). For this reason alone, it would be misleading to propose a scaled environmental impact ranking of different materials.

The knowledge on toxic and harmful materials has resulted in the last decades in many regulations, but new estimates and upgrading are still being accrued. In addition to a traditional competence in design, it demands from the designer an extended knowledge about correlated normative and actual adoption of rather general precautionary principles.

Table 8.2 gives the guidelines to *select nontoxic and harmless materials* as defined and adopted by the DIS research unit.

Table 8.2 Guidelines to Select Nontoxic and Harmless Materials

Select Nontoxic and Harmless Materials
• Avoid toxic or harmful materials for product components • Minimize the hazard of toxic and harmful materials • Avoid materials that emit toxic or harmful substances during preproduction • Avoid additives that emit toxic or harmful substances • Avoid technologies that process toxic and harmful materials • Avoid toxic or harmful surface treatments • Design products that do not consume toxic and harmful materials • Avoid materials that emit toxic or harmful substances during usage • Avoid materials that emit toxic or harmful substances during disposal

From Vezzoli and Manzini (2007, 2008).

Another associated question that arouses comparative ambiguity is the *naturalness* of materials. This ambiguity, with its roots in terminology, which has been and still is accepted by many, claims that a *natural* material has by default no environmental impact whatsoever, or at least has a smaller impact than synthetic materials. This argument, as it is understood now, is wrong for two reasons. First, in nature toxic and harmful substances are in abundance (still now nature is the cause for more toxic substances than humans, who simply alter them thus only recontextualize them inside the mechanics of production and consumption). Second, practically all *natural* materials are subjected to a series of processes in order to become usable by the product production, and all those processes have their own environmental impact. Finally, if we want to highlight environmental advantages of so-called *natural* materials, we may conclude that they are more renewable and generally more biodegradable than synthetic materials.

Select renewable and biocompatible materials

An explanation is needed on material (and resources more generally) renewability. Timber is a renewable material, but the same type of wood can be procured from many different areas: some of them under planned and controlled exploitation, while others are not, i.e., leading to deforestation. So the very same material can be qualified as renewable in the first case, and not renewable/non-reproducible in the other case. It can be summarized that the renewability depends upon both the specific *regrowing* speed and the *extraction frequency*. Therefore, we can assume the following definition (Vezzoli, 2010): *a resource is renewable when the acquisition rate is smaller than the natural regrowing rate*.

It has been observed (Sachs et al., 2002; Sachs and Santarius, 2007) that when materials (and all natural resources more in general) are locally based (namely, locally extracted and locally preproduced by leaving the added value to the local communities), local socioeconomic stakeholders involved in the extraction, transformation, and sale of materials pay far more attention to preserving their renewability. The obvious underlying reason is that their economic subsistence depends not only in the short term, but also in the long term on these materials. Therefore, they are not in favor to exhaust them quickly. Therefore, it happens that most of the time the selection of locally based and renewable material is at the same time environmentally and socioethically sustainable.

Another subject that has taken some time to be understood properly is material *biodegradability*: an environmental quality that has raised many misinterpretations. In fact, however important it is for the materials to be *reintegrable* within ecosystems, for many products biodegradable materials might pose a problem in the sense of a premature expiration date, which in turn creates new processes to preproduce, produce, distribute (the new product going to substitute the old one), and dispose (the old product).

Table 8.3 contains the guidelines to *select renewable and biocompatible materials*, as defined and adopted by the DIS research unit.

Improve lifespan of materials

To *improve the lifespan of materials* means to design in a way that valorizes material from disposed products; rather than ending up in landfills, disposed products can be reprocessed to obtain new secondary raw materials (recycling or composting), or incinerated to recover their energy content.

Table 8.3 Guidelines to Select Renewable and Biocompatible Materials

Select Renewable and Biocompatible Materials
• Use renewable materials • Avoid exhaustive materials • Use residual materials of production processes • Use retrieved components from disposed products • Use recycled materials, alone or combined with primary materials • Use biodegradable materials
From Vezzoli and Manzini (2007, 2008).

We use the term recycling when secondary raw materials are used to manufacture new industrial products and composting, when secondary raw materials are made into compost.

In all these cases, the environmental advantage is doubled: first, we avoid the environmental impact of disposing of materials in landfills; second, a material resource or energy is made available for the production phase of a new product, i.e., avoiding the impact from the extraction to processing of a corresponding quantity of materials and energy from virgin natural resources. The avoided impact of these processes can be considered as an indirect environmental advantage.

While designing for (postconsumption) recycling, we have to recognize its different phases:

- the collection;
- the transportation from collection place to recycling site;
- the separation, meaning the disassembly and/or crushing of materials that are not compatible: metals from plastic, and the plastic that cannot be recycled together;
- the identification of various materials;
- the cleaning, for example, from contaminating substances or adhesive labels;
- and finally the production of secondary materials.

All this means that designing for recycling should facilitate all those phases. Or rather that design for the improvement of the lifespan of materials does not mean simply choosing materials with efficient recycling or combustion technologies, but designing to facilitate collection and transport after use, labeling of materials, minimizing the number of incompatible materials, and facilitating their separation and cleaning.

A clarification on the recyclability of materials: it is common to hear that a certain material is 100% recyclable. Often these statements have no real meaning. In fact, in one way or another, nearly all materials are recyclable.

Therefore, the recyclability depends obviously on specific material characteristics, namely, the performance recovery potential and the relative costs, e.g., metals recover their performance better than plastics after recycling.

Table 8.4 Guidelines to Improve Lifespan of Materials

Adopt the cascade approach
• Arrange and facilitate recycling of materials in components with lower mechanical requirements • Arrange and facilitate recycling of materials in components with lower aesthetical requirements • Arrange and facilitate energy recovery from materials throughout incineration
Select materials with the most efficient recycling technologies
• Select materials that easily recover after recycling the original performance characteristics • Avoid composite materials or, when necessary, choose easily recyclable ones • Engage geometrical solutions like ribbing to increase polymer stiffness instead of reinforcing fibers • Prefer thermoplastic polymers to thermosetting • Prefer heat-proof thermoplastic polymers to fireproof additives • Design considering the secondary use of the materials once recycled
Facilitate end-of-life collection and transportation
• Design in compliance with product retrieval systems • Minimize overall weight • Minimize cluttering and improve stackability of discarded products • Design for the compressibility of discarded products • Provide the user with information about the disposing modalities of the product or its parts
Material identification
• Codify different materials to facilitate their identification • Provide additional information about the material's age, number of times recycled in the past, and additives used • Indicate the existence of toxic or harmful materials • Use standardized materials identification systems • Arrange codifications in easily visible places • Avoid codifying after component production stages
Minimize the number of different incompatible materials
• Integrate functions to reduce the overall number of materials and components • *Monomaterial* strategy: only one material per product or per subassembly • Use only one material, but processed in sandwich structures • Use compatible materials (that could be recycled together) within the product or subassembly • For joining use the same or compatible materials as in components (to be joined)

(*Continued*)

Table 8.4 Guidelines to Improve Lifespan of Materials *(continued)*

Design for incompatible materials disassembly

Overall architecture:
- Prioritize the disassembly of toxic and dangerous components or materials
- Prioritize the disassembly of components or materials with higher economic value
- Minimize hierarchically dependent connections between components
- Minimize different directions in the disassembly route of components and materials
- Increase the linearity of the disassembly route
- Engage a sandwich system of disassembly with central joining elements

Shape of components and parts:
- Avoid difficult-to-handle components
- Avoid asymmetrical components, unless required
- Design leaning surfaces and grabbing features in compliance with standards
- Arrange leaning surfaces around the product’s center of gravity
- Design for easy centering on the component base

Shape and accessibility of joints:
- Avoid joining systems that require simultaneous interventions for opening
- Minimize the overall number of fasteners
- Minimize the overall number of different fastener types (that demand different tools)
- Avoid difficult-to-handle fasteners
- Design accessible and recognizable entrances for dismantling
- Design accessible and controllable dismantling points

Engage reversible joining systems
- Employ two-way snap-fit
- Employ joints that are opened with common tools
- Employ joints that are opened with special tools, when opening could be dangerous
- Design joints made of materials that become reversible only in determined conditions
- Use screws with hexagonal heads
- Prefer removable nuts and clips to self-tapping screws
- Use screws made of materials compatible with joint components, to avoid their separation before recycling
- Use self-tapping screws for polymers to avoid using metallic inserts

Engage easily collapsible permanent joining systems:
- Avoid rivets on incompatible materials
- Avoid staples on incompatible materials
- Avoid additional materials while welding
- Weld with compatible materials
- Prefer ultrasonic and vibration welding with polymers
- Avoid gluing with adhesives
- Employ easily removable adhesives

Table 8.4 Guidelines to Improve Lifespan of Materials *(continued)*

Codesign special technologies and features for crushing separation: • Design thin areas to enable the taking off of incompatible inserts, by pressurized demolition • Codesign cutting or breaking paths with appropriate separation technologies for incompatible materials separation • Equip the product with a device to separate incompatible materials • Employ joining elements that allow their chemical or physical destruction • Make the breaking points easily accessible and recognizable • Provide the products with information for the user about the characteristics of crushing separation *Use materials that are easily separable after being crushed.* *Use additional parts that are easily separable after crushing of materials.*
Facilitate cleaning
• Avoid unnecessary coating procedures • Avoid irremovable coating materials • Facilitate removal of coating materials • Use coating procedures that comply with coated materials • Avoid adhesives or choose ones that comply with materials to be recycled • Prefer the dyeing of internal polymers, rather than surface painting • Avoid using additional materials for marking or codification • Mark and codify materials during molding • Codify polymers using lasers
Facilitate composting
• Select materials that degrade in the expected end-of-life environment • Avoid combining nondegradable materials with products that are going to be composted • Facilitate the separation of nondegradable materials
Facilitate combustion
• Select high-energy materials for products that are going to be incinerated • Avoid materials that emit dangerous substances during incineration • Avoid additives that emit dangerous substances during incineration • Facilitate the separation of materials that would compromise the efficiency of combustion (with low energy value).
From Vezzoli and Manzini (2007, 2008).

But the recyclability depends also on the way a material is *fitted* into a product, i.e., if it is easy to separate it from others; in this sense we can say that it depends on the product architecture and assembly. We could have a material capable of well recovering its performance, but very difficult and inconvenient to be separated from adjacent materials. In such cases, they cannot be called recyclable materials.

Similarly, recyclability depends on every recycling phase, beginning from collection and transportation.

We could have a material capable of well recovering its performance, easy to be separated from other materials, but far too costly to be collected and transported to the recycling sites. In this case, we again cannot assert that they are recyclable materials, because their recycling will not be fulfilled because of economical reasons.

Finally, treating design for recycling properly demands a transition from estimating the recyclability of materials to the economic and technological feasibility of the whole encompassed process. Thus, the design choices have to focus on morphology and architecture of the product and design correlated to the entire path of the material to be recycled. Design for recycling has to cover a set of indications that aims to facilitate every single stage: collection, transportation, disassembly, and eventual cleaning, identification, and production of secondary raw materials.

Table 8.4 presents the guidelines to *improve the lifespan of materials* as defined and adopted by the DIS research unit.

CONCLUSIONS: MATERIAL SELECTION IN DFS

Sustainability asks for radical changes, to such a degree that even system innovations are required. This understanding has moved, in the last decades, the attention of design research from the selection of materials with a low environmental impact toward product LCD, onward to design for ecoefficient PSSs and more recently to design for social equity and cohesion.

So forth, when speaking about material selection and DfS, it is necessary to bear in mind the overall picture described above, otherwise we may encounter the risk of believing that DfS is just a matter of materials selection.

This is not to say that adopting a more systemic approach to design means we do not have to care about the selection of materials with a low environmental impact any more. Definitely not. Even adopting a system design approach, materials need to be selected to reduce the environmental impact of products (in relation to life cycle stages and the functional unit); in turn, products could be designed ecoefficiently as far as they are conceived within a PSS design approach (to deliver a satisfaction unit). Finally, we have seen in this chapter that the selection of materials could even be addressed to improve social equity, when they are locally based and renewable.

To conclude, even in a system DfS approach (Vezzoli, 2010), the "material" side (i.e., materials selection) is of key importance.

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CHAPTER 9

Designing with Waste

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CONTENTS

In 1969, the designer Richard Buckminster Fuller (Fuller, 1969) compared the Earth to a spaceship on which "we are all astronauts" dependent on finite resources. The resources to sustain life on Earth undoubtedly need to be used carefully and managed effectively but much has changed in the successive generations since the statement was made. Buckminster Fuller implied that the spaceship would not be able to collect additional supplies in the future and that there is a global responsibility to adopt a more sustainable approach. James Lovelock's Gaia theory that the Earth has an innate ability to self-regulate might not, as Victor Papanek (1995) inferred, be something that is beneficial to all the inhabitants of the planet: what counts toward the survival of the astronaut is fundamentally different to that which ensures the survival of the spaceship. It is becoming increasingly important to recognize this (Leonard, 2010).

The global situation is in a constant state of flux that needs to be constantly monitored and evaluated. For example, projections through the Global Footprint Network (http://www.footprintnetwork.org), a think tank promoting sustainability, demonstrate that the current consumption of resources perilously outstrips availability and that the burgeoning demand is presently anticipated to require the resources of two Earths by 2030. Even in the late 1960s, with a much smaller global population, the Earth was already argued to be at the upper limits for sustainability (http://www.footprintnetwork.org/en/index.php/GFN/page/footprint_basics_overview/).

Whatever the accuracy of the figures, it is clear that one of the challenges facing us is that of the lack of "additional supplies"; resource depletion becomes an increasingly pressing matter. "Reduce, Reuse, and

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Recycle" is usually seen as the predominant alternative to such ever-increasing reliance on virgin materials. Upcycling of materials can be considered to be an amalgamation of all these processes and is accepted as a potentially viable option in the search to reduce any unnecessary resource expenditure. Upcycling provides an opportunity for discarded and waste products to be transformed into new, reconfigured, repurposed, and enhanced items. Some versions of upcycling are quite commonplace and somewhat ephemeral. For example, jewelry and bags made from the scavenged foodstuff labels, and sometimes known as "trashion", through to new products as diverse as soap, rugs, lamps, furniture, and even whole buildings.

Although upcycling is not a mass production phenomenon it does ask questions about how some globalized products are mass produced. Can the creation of localized upcycled products using local resources and techniques compete with mass production? With many designers engaging with the idea of upcycling, and with a steady stream of upcycled products entering the market, the prejudices that have hindered a general and widespread acceptance of products created from waste have certainly begun to be challenged.

USE LESS AND USELESS

The need to reduce carbon emissions and be creative in the utilization of natural resources continues to be of paramount importance and protocols to address the deficit need to be sourced. Rudimentary and radical commitments to change would appear to have the potential to assist the current situation of more resources being exhausted than replenished.

Designers have always been tasked with a responsibility to improve quality of life and can influence the sustainable use of resources through the ethical and moral decisions related to their creative outputs. Their ability to think and to consider available options before any specific commitment to materials or processes provides the opportunity to ensure that appropriate directions can be followed without the need to squander resources and compromise the environment.

Maslow's well-known "hierarchy of needs" (Maslow, 1943) remains a simple, powerful, and useful method of evaluating moral responsibility. The primary needs of individuals should be the foremost consideration to ensure that basic requirements are made available to all. The current overshoot and unbalanced distribution of global resources conflicts directly with Maslow's hierarchy of needs. Fundamental resources continue to be directed to peripheral and superficial causes while many elementary requirements are either ignored or overlooked.

The designer needs to be continually abreast of developments and their possible implications. An ability to comprehend core problems through primary research, and to ask pertinent and searching questions, is necessary. What is the core problem? Is the problem the same as the perceived problem? Research to fully understand what is needed is always required. Any disregard or flippant, careless appraisal of a situation or an opportunity can have an unnecessary effect. Understanding the environmental problems and an appreciation of the difficulties presented creates useful design constraints that can assist thinking and reveal options that might not have been previously considered. Adverse processes that are detrimental to the creative journey can be filtered out through such restrictions.

As with all such normative projects, the bigger picture needs to be understood if useful and informed decisions are to be made. Life cycle assessments for proposed products are known to support the evaluation process by providing valuable information related to any potential effect a designed item might cause to the environment. The process methodically considers all the individual stages of production, the consequences of use, and the approaches to be adopted for discarding an item. Although such assessments are conducted, many mass-produced products still contribute to some form of ecological damage. The "cradle to grave" or "womb to tomb" approach of monitoring a material cycle from inception to demise often reveals a detrimental abandonment of an essential resource that should be identified as a concern during the design stages rather than after the item has been created.

William McDonough and Michael Braungart's "cradle to cradle" thinking (Braungart and McDonough, 2002) recognizes the value of materials and promotes the idea of reprocessing and reusing redundant materials providing an important lease of life to a material rather than condemning it. The approach aims to avert the need to continually extract valuable, virgin material.

The importance of examining and probing every stage of the design cycle to fully comprehend the most sustainable path in developing a product should not be understated. It is increasingly necessary to relate to the end user and to recognize the scenario that a product is to be placed into while also appreciating any global implications of developing yet another product. Is the product necessary? Is it a suitable use of available resources? Is it sustainable?

Life cycle analysis can reveal contestable results that themselves may suggest differing priorities in terms of materials choices, engineering decisions, and design content (Maycroft, 2000). A product will often demonstrate positive and negative traits and rarely can an emerging product be considered to be entirely "green". Reducing any individual area of concern often concludes in compromise. A product can appear environmentally friendly due to the material it has been created in but the advantages of the material might be canceled out through contradictory distribution or manufacturing practices (Cooper, 2010).

A need to share information and experiences, to develop empathy of the overarching problem as well as the localized issues is becoming increasingly significant. Design cannot be a process of creation without responsibility and designers cannot operate in an information void. The consequences of every action need to be evaluated, understood, and holistically viewed.

The simplest method to preserve resources is to reduce the amount being used. Use less. A design that is fully appraised can be configured to ensure that it does not use excessive material and that it is able to embrace more acceptable processing methods or eliminate them altogether.

Consideration of, and a strong commitment to, durability rather than as an ephemeral proposal at the design stage can also contribute to an overall reduction in resource expenditure as the need to replace items is either arrested or completely negated (van Hinte, 1997). A reduction in material does not need to imply the development of an inferior product but rather can be seen as an opportunity for the enhancement of design thinking. This can be the case for high-end consumer products. For example, as of writing, Apple Inc. has released an updated version of their iMac computer. This variant is more than 3.5 kg lighter than that which it replaces. This has been achieved through new design, engineering, and manufacturing techniques and the result is a more powerful, efficient, and environment-legislation compliant model. Material reduction can also stimulate design thinking, while maintaining or enhancing product quality, in the development of more modest products. This has been especially evident in relation to some packaging material over the recent past. The challenge remains to transform a growing consumer antipathy toward superfluous packaging into one that similarly questions the materiality of products themselves. Significantly, material reduction can take place at different points in the process of product genesis: raw materials, discrete components, casings and fastenings, packaging, instruction and maintenance inserts, and promotional materials (Hill, 2011).

Communities with very limited resources often manage to set unparalleled examples in their resourcefulness and creativity. The products of many disadvantaged communities are not usually intended for mass production purposes but their thinking and ingenuity can provide a useful benchmark for more prosperous societies to reflect upon.

Reuse is an obvious method to conserve virgin resources and to ensure the longevity of existing artifacts where a commitment, good or bad, has been made previously. There are many different aspects to reuse, ranging from items that an individual can continually maintain and utilize, to items that can be shared or borrowed among communities. The reuse of an object might even be interoperated differently between different user groups or cultures but providing the object continues to serve a purpose this should not be a concern.

The benefit of the reuse approach is that unlike many recycling methods that require reprocessing a reuse agenda is ultimately more sustainable.

The unpalatable vanity of too many consumers that allows for a throwaway culture to exist where resources are lost without conscience should be questioned. The replacement of a complete product, discarded only because it is slightly tarnished, is unacceptable. What is wrong with a product having some battle scars that tell a story? How long does it take for any product to become visually contaminated? Objects of historical importance often appeal more when they are able to portray a story through such imperfections (see Chapter 11, by Karana and Rognoli).

Some disposal of material is inevitable. However, any reduction is preferable as it results in less pollution. When a commitment is made to a material it should be sustained wherever possible. Common sense in developing products should prevent the environment from being unduly compromised.

USE REFUSE

The exhaustive utilization of irreplaceable resources to make items without considering and appreciating what already exists is clearly a continual problem. The ability to use the imagination and embrace preformed waste items should in essence be no different from the utilization of any material. Removing the blinkers and the bias of what can be done with waste material opens up a wealth of opportunity. The results are perhaps not what a designer would normally produce if there were no constraints but any emerging products may capture the imagination.

The initial impression of any waste material can seem to be restrictive but applying design principles as with any other project reveals a diversity of options. The opportunity to use waste branches from the injection molding process in Guangzhou China led to the creation of the Branch Chandelier (2012), Figure 9.1, which relied on the clipping together of sections without the need for any processing. The design was able to take inspiration from the innovation demonstrated by individuals in the street collecting and upcycling a multitude of waste items.

An ignorance of the waste materials available means opportunities are missed despite the situation where the vast majority of rejected or reclaimed material could be converted into a desirable and improved object. While industrial designers have for generations tackled the issue of incorporating refuse and abandoned objects into their outputs it has tended not to be a mainstream activity. The practice of using sourced objects has perhaps been more of a statement or reaction to a particular style or accepted trend, a form of antidesign to challenge meaningless products. The reaction against the profusion of impersonal, austere products in the late 1970s prompted a design dialogue to emerge that subsequently influenced a generation and managed to steer creativity and design thinking into many alternative and contrasting directions. Eclectic characteristics were assembled to defy conventions and to summon attention. The unexpected approaches, and the "dare to be different" attitude, cast aside the sterile conservative attitudes that had developed and significantly affected global design thinking. Such resistance to diversification is usually thwarted until a specific statement is presented that is difficult to ignore. The contemporary approaches to upcycling are currently becoming increasingly difficult to discount.

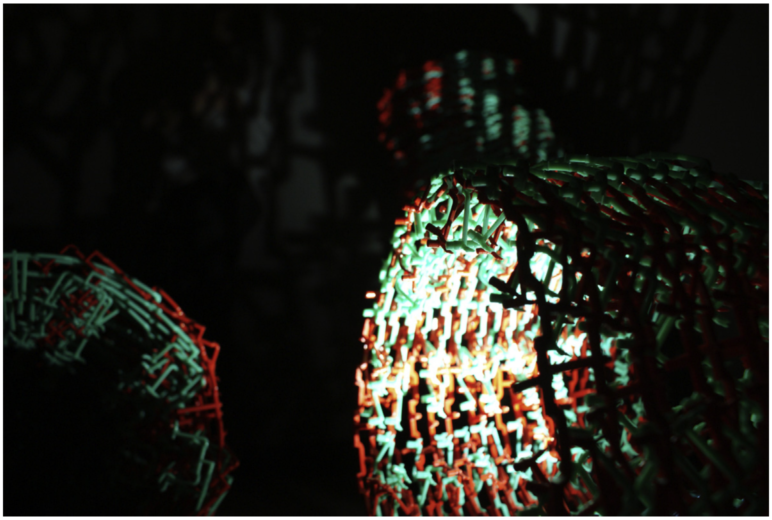

FIGURE 9.1
"Branch Chandelier" designed by Joe Bowden, Evie Kemps, and Zhang Wei of Redden. The British Council Sino-UK Higher Education Collaboration project, Guangzhou China (2012).

Aesthetic appeal too often becomes dominant over ethical appeal, with a consequence that too many frivolous and unnecessary mass-produced products are created. The abundance of sister products, products that function alike and are fundamentally identical to each other, need to be questioned. This waste of resources on so many fronts could have been saved or redirected to substantially more appropriate causes and potentially less competitive markets. It is a concern when these products, which are created to appear beautiful and appeal to the end user, can be so easily rejected and then not considered for incorporation into future products. What is it that suddenly turns them from a desirable object to an unacceptable object?

There are multiple materials, in multiple forms that have the potential to be utilized for other purposes and yet the vast majority are disposed of. Global acceptance of a particular product characteristic creates widespread mental baggage and preformed associations to what something can be or should be. Such perceptions can make it decidedly difficult for it to be seen or thought of differently by a wide audience. Where it is possible to reconfigure the thinking and dispel previous associations to an object, the results can be enlightening and trigger further design activity. The option not to make a change to a path that is not sustainable or has become staid would suggest an irresponsible attitude and demonstrate a lack of creative thinking. It is always possible to adopt alternative practices and to continue to create objects that delight and meet expectations.

Upcycling, as with any design process, requires an ability to appreciate materials and to push the boundaries of what is possible. It also demands communication and the development of knowledge through experience. Upcycling provides the opportunity for physical interaction and the opportunity to develop an inherent understanding of existing and yet-to-exist objects.

Creating an object that allows for alterations or components to be easily replaced or updated enables the end user to engage with the product. Why do so many mass-produced products need to be manufactured in such a fashion that they completely alienate the user and seemingly encourage disposal if a minor problem occurs? Objects can be designed for sustainable lives and still retain visual beauty.

Sentimental attachment to an object is particularly forged with the end user when the individual component parts of the item have a meaning additional to that of the completed artifact. For example, an upcycled product that is created from discarded items such as a particular soda bottle may already have an affinity with the end user even before it attains its secondary state. This bond is rarely evident in products that have been created outside of the user's own personal experiences and makes the sentimental connection less influential. Products where there is no sentimental attachment are undoubtedly easier for the user to reject.

The function of any object can be multifaceted and should not always be considered to be its most obvious feature. Function relates to an array of considerations all of which can be significant. The creation of a product from waste material can undoubtedly be beautiful and appealing but the descriptors are subjective and individual. A primary function of an upcycled product, besides responding to a direct need, is that it manages to prevent waste material becoming a pollutant. In this way, whether or not it is obvious from the product form and configuration, an upcycled product explicitly and directly addresses the sustainability agenda in a way that products manufactured from first base cannot.

Can any aspect of an emerging product be upcycled to reduce carbon emissions? If a mass-produced product is not sustainable, should not alternative solutions be explored at the design stage? The ability to instigate and create upcycled outputs is certainly not the preserve of the design industry alone. Although there are many complicated and process-intensive production methods that tend to be inaccessible to the individual, the approach to upcycling is undeniably accessible to all.

The "Honesty & Simplicity" collection created by mbrela included a variety of discarded materials that were upcycled with minor modifications. The design Dragg, Figure 9.2, used abandoned rope that had a luminescent wire inserted to create a simple but effective light. The design and process were both simple but the outcome was particularly effective.

Communities that experience hardship and shortages of basic requirements manage to demonstrate incredible ingenuity in the manner in which they are able to identify solutions to difficult situations. Abandoned and broken commodities are sourced and modestly adapted to respond to a particular need or desire. Vanity is replaced by pride as a simple and sustainable solution is discovered. Such improvisation is evident in the third world but it is not uniquely consigned to these areas. Presented with limited tools and resources, it is undeniably surprising what can be created and what decisions are made. Allotments in the United Kingdom demonstrate simple innovation and resourcefulness and are similar in this respect to favelas and shantytowns in South America. These are areas where solutions are found to immediate problems and where redundant objects are utilized in ways that supplement, extend, or even replace their original purpose. The average occupant of a favela or owner of an allotment is probably not design educated but their approach to thinking is inspirational and worthy of exploration to appreciate emerging opportunities. Improvisation is everywhere and indicators of what can be created with reclaimed objects provide valuable inspiration to the design community.

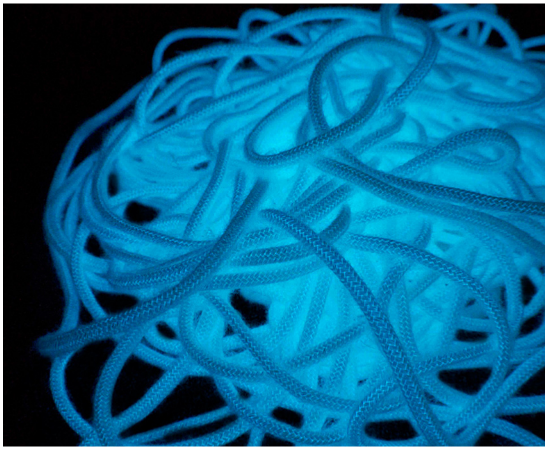

FIGURE 9.2
"Dragg light" designed by Michael Palmer for mbrela 2011.

Occasionally, improvised objects might require refinement but in essence the fundamentals are being addressed and solutions are being found.

An appreciation of design, coupled with the desire to create products related to personal encounters and experiences, provides an opportunity to develop items of worth. Upcycling provides an opportunity to merge disciplines, cultures, and experiences. Ephemeral design practices are omnipresent and provide insights into practices and procedures that could inform a wider audience. Why not use found objects? Why not consider this? Why not do that?

EMERGING BEAUTY

The ability to see the potential in waste or the materials abandoned by others provides incredible scope for a diverse array of outputs. Too often, a rejected item is perfectly suited to another application but a lack of imagination or thought means that the opportunity is lost. An increasing body of innovative designers and artists are creating products using rejected materials that manage to compete with similar outputs using only virgin materials. The outputs demonstrate incredible potential for changing the perception of waste material.

Artist/designer Stuart Haygarth combines disciplines and experience in the creation of lighting designs that transform everyday waste into products of exceptional beauty and relevance. The creations have a story to tell and an appeal that is often not evident in perhaps the more mainstream outputs of others. The materials used within the lighting appear to or communicate with the artist just how the design should evolve. Lighthouse (2009), comprising a collection of floor lamps, uses stacked waste plastic caps that have been exposed to the elements. The delicate tones of the perished plastic were seen as a positive rather than a negative contribution in forming the light. The ability to view things differently is also evident in Stuart Haygarth's two chandeliers entitled Tide (2004) and Millennium (2004). As with Lighthouse, Tide used objects found on the beach and managed to exploit the simple beauty of everyday items. Tide, created again with multiple stressed items, included combs, bottle tops, goggles, and toys. The eclectic mix of objects that many would ignore was configured to form the chandelier with incredible beauty. Millennium used dispensed party poppers that were available in abundance after the Millennium celebrations. The language of the waste material is transformed when it is viewed differently and barriers are removed. How difficult is it to view a rejected item and to understand its potential? To accomplish results such as Millennium and Tide, it undoubtedly takes experience and aesthetic judgment, but engaging with and playing with materials can direct attention toward latent potential.

Tail Light (2007), Figure 9.3, chandelier created by Haygarth used a potentially obvious material for the work, but perhaps only obvious when the designer revealed it. An ability to design provides the fundamental step between creating an object and creating an appropriate object. The use of plastic tail light covers to create the structured, geometric form is undoubtedly a considered and creative use of abandoned light covers. Similarly, ecodesigner Sarah Turner has attracted much interest in the creative outputs that she has produced using predominantly used plastic water or soda bottles. Appreciating that many of these products enter landfill Turner has produced lights such as Soda 10 and Cola 10, Figure 9.4, from 10 used drink bottles. The lights, which are collected, cleaned, and sandblasted, are then shaped into their distinctive forms before using the original plastic cap to secure the design. The

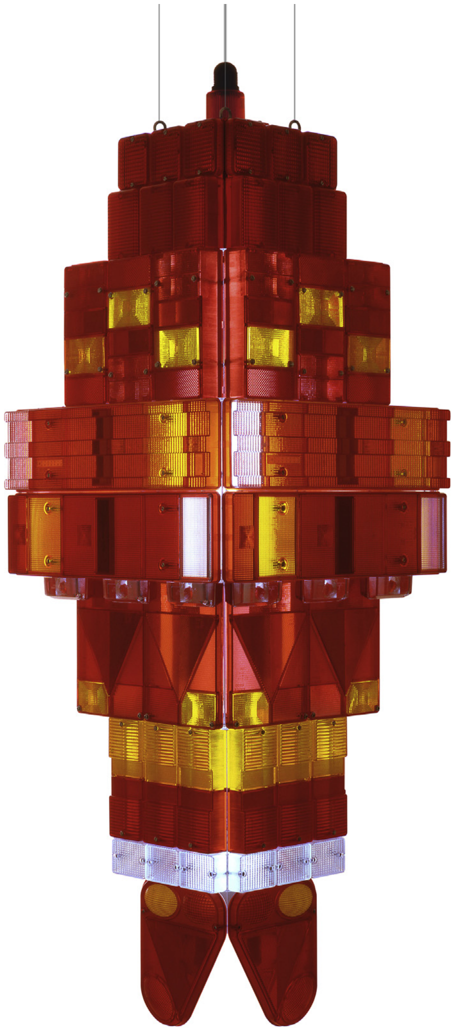

FIGURE 9.3
“Tail Light” (2007) designed by artist/designer Stuart Haygarth.

element of surprise so evident in the work of Wilcox and Haygarth is also captured in the work of Soda 10 and Cola 10. It is difficult for the observer to imagine that the lights have been created through using abandoned soda bottles and that the design required only basic material processing to create.

Stuart Walker, Professor of Sustainable Design and Co-Director of the ImaginationLancaster design research lab at Lancaster University, has conducted much research into the meaning of products and their aesthetic appeal and appreciation. Products such as “Lather lamp” and “Wire lamp” designed by Professor Walker use everyday, simple, found objects. There is no ambiguity to the designs. The

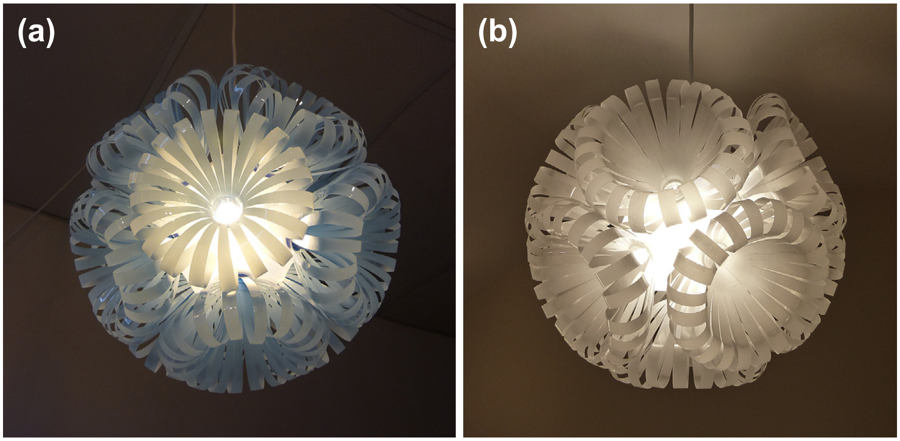

FIGURE 9.4
(a) "Soda 10" and (b) "Cola 10", designed by Sarah Turner. The designs are each created using 10 found plastic bottles.

simplicity and honesty of the design is appealing. The lights do what they intend to do and can be maintained and repaired without complication. Such designs, like so many products from disadvantaged societies, provide an indication of how products could be (or perhaps even how products *should* be), designs that are sustainable, simple, and readily understood.

Co-oproduct formed by UK designers Tracy Cordingley and Jamie Billing encourages open collaboration and dialogue associated to creative reuse and upcycling.

The Co-oproduct Internet portal promotes a "Make It Yourself" agenda with the intention of encouraging others to engage in the making of viable products from waste materials such as "Udderly Beautiful" by Nicole Krystal, which uses reclaimed milk bottles. The viral communication of upcycled designs inspires others to rethink the potential of reclaimed material, and its approach should be lauded. Indeed, as societies continue to embrace and engage with an emerging generation of commodities through upcycling, focus should be given to designing products for an upcycled journey.

CONCLUSIONS

Unknown "creatives"—those individuals who understand and can respond to an immediate problem—are solving everyday needs through experimentation and curiosity. These individuals often work in isolation but unconsciously form part of a global community that collectively creates large numbers of unique items. Their outputs use locally sourced waste material or found objects to create items that relate to their specific neighborhood but can be transferred to other cultures and communities for interpretation. The products being produced are often simple, effective, and straightforward to understand. These are products that do not have to respond to complicated criteria to meet the expectations of a wide audience. The upcycled products can be specific and personal. This generation of products relates to the originator and has meaning. They tell a story and have an inherent sentimental value. These products can be repaired, maintained, and improved without needing to dispose of the entire object and the products are naturally evolving as the supply of waste material changes. However, the appeal of the upcycled generation of products, when individual user experience is coupled to broader design content, is difficult to assess.

Is it possible for upcycling to become a distributed mass production system? The approach is gaining momentum and being accepted as an understanding and respect for waste material increases. The need to preserve virgin materials and resources will always be of paramount importance irrespective of developments. The Buckminster Fuller spaceship might still be unable to collect more resources but the current generation of astronauts are becoming versed in renewable energy and demonstrating an understanding of the need to conserve and preserve through global communication.

Acknowledgments

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CHAPTER 10

Meaningful Stuff: Toward Longer Lasting Products

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CONTENTS

You peer through last season's IKEA blinds to see the neighbor's parking space, where a sulking Dyson now garnishes a skip filled with construction rubble, dotted with the broken fragments of a once-craved avocado suite. Next to it is a sun-yellowed cathode ray tube monitor showing ultraviolet decay, like a scorched tourist nearing the journey's end. Never before have we owned so much, wanted so much, and wasted so much. In a world smothered in people and products it must be questioned what—beyond a conventional understanding of functionality—is all this "meaningful stuff" really for? Why does it transform into "meaningless rubbish" so quickly. What is it that we actually seek through this world-breaking process?

This chapter will focus not so much on "what" we do as consumers, but "why" we do it, leading to a broader evolutionary and behavioral discourse on the meaning and role of objects in our lives, drawing into focus the essential relationship between our enduring need for material experiences, and the impacts this has on the natural world.

This chapter examines the meaningful proxies, triggers, and metaphors embedded within material experiences, exposing alternative understandings of the immaterial culture underpinning our stuff, and the manifold dialogues we are continually engaged in with the designed objects that touch our lives.

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ALTERING THE PARAMETERS OF LIFE

The "made world" is a consequence—an emergent space in which the human species has progressively found ways to modify and enhance the world around us. The urban spaces we roam, buildings we inhabit, products we use, and garments we wear collectively represent our intellectual capacity to imagine a better world that is beyond our current level of experience. This innate capability to imagine a world just beyond our current level of experience, and then formulate (design) plans to realize those imaginings, is an essential determinant of what it is to be human—to reach beyond innate human limitations (Heskett, 2003).

There is nothing new about this. Throughout human history, evidence of this enduring human characteristic can be found, whether the selective rearing of high-yield livestock by our early ancestors, or the genetic modification of a given strain of fungus-resistant barley. Through millennia of *striving* to enhance the conditions for life, we have evolved our processes and practices beyond recognition.

For example, early nomadic hunters and gatherers initially used the animals and plants they found in the environment, as food. Gradually, they learned how to expand their food supplies by using processing technology (such as pounding, salting, cooking, and fermenting). After many thousands of years of hunting and gathering, the human species developed ways of manipulating plants and animals to provide better food supplies and thereby support larger populations. People planted crops in one place and encouraged growth by cultivating, weeding, irrigating, and fertilizing. Communities captured and tamed animals for food and materials and also trained them for such tasks as plowing and carrying loads (now replaced by large machines powered by fossil fuels, and controlled by just one person); later, they raised such animals in captivity (Rutherford and Ahlgren, 1991).

Professor Emeritus of Anthropology, Robert Bates Graber, tells us how biological evolution adapts species to environments, cultural evolution adapts environments to species. Ways of life can change far faster than can the species' biological makeup. For example, the advent of the steam engine, the automobile, and the computer transformed the way we live, with little or no biological evolution having taken place during that time frame. Artifacts, customs, and ideas can spread rapidly within a generation; biological evolution happens only over generations.

Graber describes how the secret of our success is *culture*. Humans have adapted to new environments, for the most part, not biologically but culturally. Culture allows us to create, within hostile environments, a "little environment" friendly to us. Control of fire, for example, meant we could create little enclaves of warmth in the coldest corners of the earth. Now, half a million years later, we live with the fish not by evolving fins and gills, but by surrounding ourselves with submarines, and we are venturing into airless space not by evolving the ability to do without oxygen, but by surrounding ourselves with space shuttles and stations. It even is conceivable that we will be able to modify other planets to suit our needs (Graber, 1995). However broad the horizon, it is clear that the roots of materiality derive from, and are shaped by, this enduring form of adaptation and evolution.

DESIGN IS DARWINIAN

Consider the term *survival of the fittest* and mental images of superior springbok, the most highly camouflaged moth and chimpanzees with slightly enlarged right brains, may emerge. Although only very slightly better adapted for survival, these important changes within a given species provide edge, and it is this thin sliver of difference that dictates the difference between life and death in the natural world.

Evolutionary pathways can also be found within the material world, and this is where the design part of this story begins. Items ranging in scale from running shoes and light fittings to aircraft and football stadiums hold an important evolutionary legacy also. However, to understand and observe this, we must look to the predecessors that define their journey. Indeed, objects have within them a legacy—or DNA—which is quite noticeable, if you are looking for it.

Take the running shoe, for example. Dissect such a product, and you will learn something of its construction, of the way it functions, and of the basic relational properties of the materials and processes that make it, as a system, perform. Yet, the information revealed through this technical exercise would be limited, as it tells us nothing of the origin, direction, drive, intention, and future of the design vision that underpins the development of this product. It also tells us very little about the meaning and value of the object in relation to users. Now, dissect 20 generations of running shoes, one per season dating back 5 years, and you will learn significantly more. You will reveal the incremental adaption that this product has undergone. You will see clearly the direction of this evolution and from this understand the values, goals, and aspirations of the design culture from which it emerged.

Depending on the typology of design, the criteria for survival will differ greatly. For mobile phones, the evolutionary pathway may be geared toward the evolution of smaller, lighter, faster, and smarter devices, whereas the evolution of sofas might be geared more toward price, style, and comfort, for example. Even with language, this process of continual adaption can be witnessed. In 1870, Darwin quoted a writer in *Nature* who described how a struggle for life is constantly going on among the words and grammatical forms in each language. The better, the shorter, the easier forms are constantly gaining the upper hand, and they owe their success to their own inherent virtue (Darwin, 1870).

In an article entitled "Darwin among the Machines", Samuel Butler raised the possibility that machines were a kind of *mechanical life* (Butler, 1863) undergoing constant evolution through the toiling of their creators. Although much of Butler's writings were satirical in nature, they engaged forcefully with some important philosophical questions relating to conceptualizations of nature as a mechanical system. In *Erewhon* he later argued the improvement of machinery relies on competition, the destruction of inferior machines, and the creation of better machines (Butler, 1872). It is important to note that almost one and a half centuries later, we follow the same doctrine, although our methods of destroying and creating machines have improved—marginally.

This is not to say that objects evolve in the same way as plants or animals. Adrian Forty argues that artifacts do not have a life of their own, and there is no evidence for a law of natural or mechanical selection to propel them in the direction of progress (Forty, 1986). Indeed, objects are not autonomous, sentient beings—they are a consequence. Yet, the made world is the manifestation of a continually evolving and adapting humanity, and in this sense, is connected to some organic form of evolutionary process, albeit, our own. It is a consequence of the collective values held by the people who created it, and their perception of the values held by the people they created it for.

Nobel Prize-winning biologist Peter Medawar describes the steady, incremental evolution of tools over time. Medawar claims that this kind of evolution embodies a learning process—a striving for improvement. In this way, the evolution of the objects, materials, spaces, and systems that constitute the made world can be understood as a consequence of learning and growth—a steadily unfolding story of our progression as a species.

WAKE OF DESTRUCTION

Owing to the evolutionary drive toward a faster, lighter, brighter, and more technologically advanced material world, humans have wreaked havoc throughout all natural systems that support life on earth. Through our collective pursuit of modernity, we have wreaked unprecedented levels of destruction throughout all natural systems that support life on this planet. Since the mid-eighteenth century, more of nature has been destroyed than in all prior human history (Hawken et al., 1999).

Our species reached full behavioral modernity about 50,000 years ago, yet during the past 60 years alone we have stripped the world of a quarter of its topsoil and a third of its forest cover. In total, one-third of all the planet's resources have been consumed within the past four decades (Burnie, 1999), all in the name of development and progress. As an inventive species, we can consider ourselves fortunate to have inherited a 3.8 billion-year-old reserve of natural capital (Hawken et al., 1999). Within the past 150 years, we have mined, logged, trawled, drilled, scorched, leveled, and poisoned the earth, toward the point of total collapse.

One does not need to be an ardent environmentalist to see that there is little or no logic to the way we relate to our environment. We clear carbon absorptive forests, to grow methane-producing meat, and smother vast areas of biodiverse wilderness with ecologically inert urban sprawl, riddled with mazes of oil-dependent highways. Examples such as these are commonplace, and one could easily fill an entire chapter just with horror stories such as these. Yet, however many examples you come across, one thing connects them all: they are each the result of an outmoded economic paradigm in which ecological systems are assigned zero monetary value. In the *natural capital* model, the world's economy is located within the larger economy of natural resources and ecosystem services that sustain all life, including us. This indicates that we should attribute value to things such as hydrocarbons, minerals, trees, and microscopic fungi, in addition to human resources, skills, buildings, and energy.

As the design and fabrication of the material world races opportunistically forth, we as users eagerly await the next, next thing. Duped by the illusion of progress we continue to spend money we do not have on things we do not need, and the wheels of conventional capitalism rotate with a familiar ease. This continual making and remaking (or selling and reselling) of the world ensures that the consumer appetite for fresh material experiences is sustained; swarms of *just noticeably different* goods hold us in a frenzied, childlike state of suspension reminiscent of bedtime on Christmas Eve. Anxious to keep up, consumers scramble to update their wardrobes, replace their trainers, refit their kitchens, and trade in their phones. The throughput of materials and energy required to support this process are unthinkable.

Resources (as we like to call matter for which we have a commercial use) are being transformed at a speed far beyond the natural self-renewing rate of the biosphere, and in the past six decades we have consumed, poisoned, corrupted, destroyed, or incinerated the vast majority of them.

Despite the enormity of these sizeable and thorny problems, it is important to remember that they are symptoms of a deeper behavioral ailment, latent in us all. Furthermore, in a postawareness raising era, it is essential that we do not scream, shout, and thump tables over this. As the Navajo proverb goes, *you can't wake a person who is pretending to be asleep*. Most people are already aware of this, although they might not be familiar with the fine grain detail of the facts and figures.

Sociologist Robert Bocock tells us that consumption is founded on a lack—a desire always for something not there. Postmodern consumers, therefore, will never be satisfied. The more they consume, the more they will desire to consume (Bocock, 1993). Bocock, whose work examines the contribution of leading writers in the field, including Veblen, Simmel, Marx, Gramsci, Weber, Bourdieu, Lacan, and Baudrillard, claims that consumer motivation, or the awakening of human need, is catalyzed by a sense of imbalance or lack that steadily cultivates a restless state of being; material consumption is therefore motivated when discrepancies are experienced between *actual* and *desired* conditions. The types of consumptive behaviors that these conditions provoke range in scale from major lifestyle shifts such as buying a larger property in a more affluent part of town, or something less dramatic, such as treating yourself to a new toothbrush. Indeed, the myriad forms of consumption that derive from this phenomenon are varied, yet the root motivation of the consumption is surprisingly consistent.

Of course, when new things are acquired, older things must be ejected from one's material empire, to make room, so to speak—out with the old, in with the new. This has led to the development of an increasingly "disposable" character in material culture and design. Just over a century ago, disposability referred to small, low-cost products such as the Gillette disposable razor or paper napkins, whereas today—largely through the efforts of industrial strategy and advertising—it is culturally permissible to throw anything away, anything from TV sets and vacuum cleaners to automobiles and an entire fitted bathroom. It should come as no surprise then that landfill sites, and waste recycling facilities, are packed with stratum upon stratum of durable goods that slowly compact and surrender working order beneath a substantial volume of similar scrap. Even waste that does find its way to recycling and sorting centers frequently ends up in stockpiles as the economic systems that support recycling and disassembly fail to support them. For example, about 250,000 tons of discarded but still usable cell phones sit in stockpiles in America, awaiting disposal (Slade, 2007).

Bernard London first introduced the term "planned obsolescence" (London, 1932)—also known as "death dating". Since then, interest in the lifespan of material experiences, from paper clips to pavilions, has steadily increased to become a crucial constituent of contemporary design discourse today (Cooper, 2002). As Slade forcefully argues in his rousing book, *Made to Break: Technology and Obsolescence in America*, the concept of disposability was in fact a necessary condition for America's rejection of tradition and our acceptance of change and impermanence (Slade, 2007). By choosing to support ever-shorter product lives, he argues that we may well be shortening the future of our way of life as well, with perilous implications for the very near future.

IMPERMANENCE IS NATURAL

In our pursuit of permanence, we are fundamentally at odds with the most essential underlying principles of the natural world—change. Change is part of the basic nature of all things. Whether we are talking about major changes in state, such as the demolition of a 40-storey block (one minute it is there, the next it is not) or something more discreet, such as your fingernails growing—change is all around us. In psychophysics, the term *just noticeable difference* is helpful in defining the smallest detectable difference between a starting and secondary level of a particular sensory stimulus (Norman, 2011), and draws useful distinction in describing minute changes in a given material, object, system, or experience.

If you take a look around you, everything that your eyes fall on, will change—from the glass in those windows to the concrete of the building you can see through them. All this is changing. Of course, our experience of the everyday tends to happen through a series of fleeting glimpses, which provide a fragmented, artificial portrayal of reality. These passing snapshots capture isolated moments in a far longer and more complex timeline of an object, material, or space. Only through sustained engagement with a given thing—be it a house, armchair, car, or a pen—can we begin to understand it in the lengthier context of flow and change, over time.

Change and the impermanence of all things has forever troubled us humans—that whispered taunt, just beneath the level of awareness, that reminds us of our own mortality, and that of all things on earth. As streams of matter and energy flow continuously in and out of each other, we realize that the one constant in all of this is change itself. The more we attempt to overcome this fact, the less in tune with natural processes our thinking becomes, and the more alien our resulting practices become.

In evolutionary biology, it is not the strongest species that survive, nor the most intelligent, but the most responsive to change. In resilience thinking, this innate capacity to absorb disturbance, and accept change (rather than defensively resist and block it), is key to success. In the made world, however, this is sorely misunderstood, and the ever-present tension that exists between states of *change* and *stability* is generally considered at odds with one another.

As if to prove our supremacy over natural laws, we fabricate the made world as though it can be fixed, set in place, and frozen. Through this, we form expectations of permanence, of things that last for centuries, unchanged. In an attempt to transcend the inevitability of change, we fabricated an alien world of durable metals, polymers, and composite materials, immune to the glare of biological decay (a reflection of our own desire for immortality, some might say); these materials grossly outlive our desire for them (Chapman, 2005), largely due to their inability to change and evolve, as our needs as users change and evolve.

Even with thoughts and ideas, the pursuit of fixed, solidified ideologies are highly prized. The level of value assigned to theories, for example, often relates directly to their longevity, and how well they have stood *the test of time*. This "resilience" is highly prized, and serves to illustrate just how afraid of change we really are. When describing the metaphysics of “rigor”, John Wood tells us how our desire to believe in rigor coincides with a popular idea of rigidity as a paradigm of the so-called real world (Wood, 1999). We continue to speak of “firm foundations” and use material metaphors such as “concrete”, “iron clad” and “material” to elevate the status of thoughts and opinions.

MATERIALS AND MEANING

So what is the role of materials in the creation of meaningful stuff? Materials mediate the aging process in a tangible and immediate way, and in this sense they play a critical role. However, the social values affixed to the aging of material surfaces are intensely complex and somewhat genre-specific—digital products tend to occupy a synthetic and scratch-free world of slick polymers, while footwear enjoys a more carefree and flexible space. Natural fiber carpets age badly, while oak floors are practically at their worst when new; leather-bound books improve like fine wines, whereas conventional hardbacks appear dog-eared and tatty in a matter of weeks.

Despite these peculiarities, patina is a necessary design consideration to assist the extension of product life spans in graceful and socially acceptable ways. Indeed, products must be designed to grow old gracefully, yet with such a multitude of variables, the question must be asked: is the sustainability of narrative experience really as simple as a dint here and a scratch there?

It is important to note here that patina is not an issue to do with material resilience or durability, but rather, a societal preoccupation with what an appropriate condition is for certain typologies of material and objects to be in. In other words, sometimes it is acceptable for a given material to develop patina, and sometimes it is not—leather handbags are accepted when scuffed and marked, polyvinyl chloride ones are rejected, for example; cars should not be dinted and scratched, unless they are vintage cars and then its considered *charming*, etc.

We must specify materials in a way that is *appropriate to the genre*, creating meaningful synergies between the tangible material experience of an object, and the societal expectation of that genre of object, and material. Designing products with the capability to deliver complex enduring narrative experiences is not simply a matter of specifying materials that age well, although this is a part of it. Instead, provocative design concepts must emerge that challenge our social desire for a scratch-free and box-fresh world, illustrating how the onset of aging could concentrate rather than dilute the experience of an object (see Chapter 11, by Rognoli and Karana).

TOWARD MEANINGFUL STUFF

As we stampede giddily forth in the seemingly inexhaustible pursuit of newer shinier material experiences, we leave behind a trail of waste. The majority of these abandoned items are neither broken nor dysfunctional. Rather, these orphans have been cast aside before their time, to make way for newer, younger models in an adulterous swing we call *consumerism*. Indeed, as the emotional needs of the user relentlessly grow and flex, the plethora of *stuff* deployed to satisfy those needs remain relatively frozen in time; the mountain of waste and ecological destruction this single inconsistency generates has yet to be fully understood.

If you drill down into the experiential nature of an object you reveal layers of meaning, so to speak, some of which are glaringly obvious and readily identifiable, while others lurk much more deeply, and are harder to spot. Material things do not *contain* meaning, but rather, they trigger meaningful associations within the perceiver. This is because meaning is a construct, and as such, there can be no meaning other than that which we create. Humans are continually unconsciously forming judgments about the world around them. These judgments may relate to the quality of an object, the temperament of a stray dog, the wealth of a total stranger, or the quality of this book, for example. When interviewed, users are often unable to say exactly what it is about an object that they are noticing. Nevertheless, the opinions flow like water, and shape the nature of their behavior in powerful ways. Indeed, although these mental processes may seem subtle, even negligible at times, their consequences are profound in shaping our experience of the everyday (Chapman, 2012), and the way in which we relate with the material world.

In design, we are familiar with seeing the world in this way. We understand that objects are so much more than the sum of their parts; they are signs, functions, meanings, and styles. Seldom are they discussed purely as inert material entities devoid of character, as this is not their intention—both from the consumers' and the designers' points of view. As Julia Lohman describes, when communicating through objects the meaning is created through the materiality of the object. The materials become words; the design becomes the syntax. The piece speaks without the detour of language (Williams, 2012).

In *Emotionally Durable Design* (2005), we are told how landfills are packed with stratum upon stratum of durable goods that slowly compact and surrender working order beneath a substantial volume of similar scrap. There would, therefore, seem little point in designing physical durability into consumer goods, if consumers lack the desire to keep them. As a strategic approach to sustainable design, emotionally durable design reduces the consumption and waste of natural resources by increasing the resilience of relationships established between consumers and products (Chapman, 2009).

Indeed, the process of consumption is, and has always been, motivated by complex emotional drivers, and is about far more than just the mindless purchasing of newer and shinier things; it is a journey toward the ideal or desired self, which through cyclical loops of desire and disappointment, becomes a seemingly endless process of serial destruction. Emotionally durable design therefore provides a useful language to describe the contemporary relevance of designing responsible, well-made, tactile products that the user can get to know and assign value to in the long term (Lacey, 2009). Objects through their materiality grow old gracefully, and accumulate character and value through time. At which point, it becomes clear that *durability* is just as much about emotion, love, value, and attachment, as it is fractured polymers, worn gaskets, or blown circuitry.

CONCLUSIONS

We shape the world as a means to extend our innate human capabilities. Yet, in so doing, we are inadvertently undermining our chances of survival. Indeed, the ecological design drive is currently recalibrating the environmental credentials of the "made world", in many cases, through the generation of more "stuff", albeit greener stuff.

Prominent anthropologist, cyberneticist, and systems thinker, Gregory Bateson, notably said that the world partly becomes—comes to be—how it is imagined (Bateson, 1979). Indeed, design plays a central role in imagining the products, systems, and processes that constitute our material reality. This material world is an *emergent property* of our collective values, beliefs, and aspirations—our collective values made manifest. In this way, we can understand the world by looking at that which we have made, and then looking at our reflection cast by those objects. So, if the world becomes how we imagine it, as Bateson says, then influencing how we imagine the world must become the focus of our endeavors.

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CHAPTER 11

Toward a New Materials Aesthetic Based on Imperfection and Graceful Aging

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CONTENTS

The aesthetics of sustainability, or as named by others, "aesthetics of environmentally sensitive products" (Walker, 1995), "total beauty" (Datschefski, 2001), "green aesthetics" (Saito, 2007), "sustainable aesthetic" (Branzi, 2008) and "sustainable beauty" (Hosey, 2012), is highlighted as a fundamental issue to be taken into account in designing for sustainability and dealing with the potential impediments on that path (Dobers and Strannegård, 2005). It is emphasized as a powerful means to influence and determine behavior, attitudes, and actions in a society (Manzini, 1994; Orr, 2002; Saito, 2007; Vezzoli, 2007) and to impart the sense of new lifestyle, real sociocultural values, and the whole philosophy of sustainability (Zafarmand et al., 2003). Walker (1997) suggested that the aesthetics of sustainability is not an objective but a result of "a" or "the" system of design, which is consistent with sustainability principles. But does it really happen automatically? In other words, do products designed for sustainability reveal their sustainability credentials that easily? Without a doubt, some aspects of design for sustainability affect the aesthetics of products, such as the reduction of the material use and components, avoidance of material colorants, ease of disassembly, etc. Nevertheless, we also see an inevitable need to overcome designerly preconceptions of aesthetics (with regard to a newly introduced product) in order to express the sustainability of a product within a broader and richer aesthetic palette (Walker, 2009). Vezzoli (2010) also emphasizes that we cannot solely design iconic-environmentalist aesthetics, which is a mass of "*green recycled panda products*". Instead, we have to follow "*the pluralism of aesthetics*" that arises from sustainability values and that can be embodied in a multiplicity of forms.

> So here is a challenge, but also an opportunity, for the designers: to design products that embody their environmental values which are made aesthetically attractive through some familiar means, without simply making them conform to the popular taste which is for the most part not environmentally informed. How can the environmental value be expressed, embodied, or revealed

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> through the object's sensuous surface in an aesthetically positive manner so that we will be attracted not only by its environmental value but also by its aesthetic manifestation?
>
> **(Saito, 2007)**

In this chapter, we desire to be involved in this on-going discussion and aim to tackle Saito's clearly formulated question, taking a materials perspective. We will elaborate on how material(s) may endorse the overall expression of a product with positive sustainability credentials.

When looked at from the perspective of materials usage, one of the recent aesthetic expressions discussed in the design for sustainability domain is whether or not a sustainable product expresses "naturalness" (i.e., comes from nature and goes back to nature), particularly through its materials (Goodman, 2012; Overvliet and Soto-Faraco, 2011; Overvliet et al., 2008). As thoroughly discussed in Chapter 1, a meaning of a material is evoked by the interactions between aspects of a product (such as shape and function) and its material properties, with respect to how and in which context the material is used and who the user is. Thus, we cannot simply claim that wood, for instance, is perceived natural in every context, in every application. The type of the wood (e.g., purple wood, which genuinely has a purple color), its form (e.g., it might have a rather unusual form, which we cannot associate with wooden products), its context of use (e.g., we can interact with it within a futuristic night club) can all affect the extent to which we consider a particular wood as "natural". On the other hand, when we are confronted with the question of whether a particular material expresses "naturalness" or not, we might intrinsically place the material "in nature" and say whether or not it fits there. Following this statement, we expect to see some commonalities between the materials appraised as natural and the basic aesthetic features of nature (such as natural colors, durability, natural patterns, uniqueness, etc.), such that a material appraised as "unnatural" would be noticeably in contrast with its surroundings.

Aiming at the exploration of this statement further, in a related study we explored when a material was appraised as "natural", or whether particular patterns from nature can be detected in relation to product characteristics (Karana, 2012). We analyzed 30 materials (and the products they embody), and the descriptions of those materials, made by 30 participants who selected those materials, concerning why that particular material/product expressed naturalness. Next to the "usual suspects" such as natural colors and patterns, we found two other common aspects in the selected materials/products emphasized by the participants: (1) the materials were commonly long lasting (they can be, or have been, used for a long time) and they were consequently "worn out" due to "long-term use" and (2) the materials mostly had imperfect surface qualities (i.e., uneven, not uniform). In addition, uniqueness and traces of someone's personal life in the material (scratches, scrapes, color change, etc.) were revealed as factors playing an important role in expressing the naturalness of a material (and a product) in relation to the labels "long lasting" and "imperfect".

The results of the conducted study on naturalness triggered us to explore "imperfection" and "aging" in greater depth. Both the attributes are proposed as media to express naturalness, to trigger unique material experiences, and to create added value that can stimulate longer term attachment to products.

IMPERFECTION > UNIQUENESS

> I always try to give the material the maximum of freedom. I pretend that matter surprises me. This is the beauty that interests me: the one that appears suddenly in the course of a trial. It's an unexpected, fresh, unique, unrepeatable beauty, that enchants me.
>
> **(G. Pesce, in an interview conducted by Annicchiarico, 2005)**

Imperfection is defined as the quality or state of being imperfect; it is something flawed, defective, or incomplete (*The New Penguin English Dictionary*). Western culture has always seemed interested in perfection, in the regularity and clean lines that the development of science and technology has made possible. In fact, we could say that technological development has led, and has been driven by, a trend to perfection. The predominance of automation processes and quality controls have led to the almost total elimination of errors and imperfections. Thus, what we have witnessed is the dominance of an aesthetic model tied to perfection in every sphere of human life: the body, the style of life, artifacts, and their materials. Everything has to look beautiful in the sense of being flawless, while appearances have become more important than essence and substance.

The rising interest in imperfection in the context of industrial design is explained as a response to the all-dominating perfectionist technology of our time (Ramakers, 2002). The need to reintroduce anomalies, defects, and imperfections, all elements that can evoke the human presence, may therefore be due to the reaction against the aesthetics of mass production: always the same and almost always perfect. This enhancement of imperfection has no connection with a conceptual or aesthetic preference for manual labor and craftsmanship; it only shows a preference or liking for errors and accidents in the production process, whatever it may be, which betray traces of humanity, use, aging, wear, and tear. Valorizing imperfection is a way of expressing workaday reality and creating innovation. By bending imperfections to our will, intensifying them, and imbuing them with aesthetic value, a new image can emerge (Ramakers, 2002). This approach has been practiced by a number of contemporary designers, among them Hella Jongerius, who explores the ways to add value through defects and imperfect variations arising from industrial production. Her "B-Set" dinnerware, for instance, is one such product. It is made of porcelain and fired at ultrahot temperatures so that the finish fractures, while concurrently the shape of each bowl and plate becomes slightly modified such that no two pieces are alike. Schouwenberg, who edited a book about Hella Jongerious, commented that the result is rather a wobbly pile of serially produced one-offs: plates with a soul (2011).

Gaetano Pesce was one of the first designers to stress the importance of imperfection and deformity with regard to its expressive and symbolic potential. He has always been fascinated by things *malfatte* (literally, badly made), because these things are able to reflect human imperfection. His design style usually celebrates the beauty of the chance and the uniqueness of the imperfections caused by a manufacturing process and material where each piece is unique and original: bubbles, defects, and dimensional changes are all embraced as part of the production process. He argues that we need new customs of production that enable imperfection as a way to create difference and so find new experiences of beauty. His pots and rings are beautifully imperfect unique pieces. Pesce's "Endless" chair expresses this concept very well: it is impossible to find two identical chairs, because each of them consists of a single bead of polyurethane, extruded, poured into a mold and then hand shaped.

As Dorfles observed (2005), Pesce appropriated the principle often exalted from Zen aesthetics known as Wabi Sabi, according to which the imperfection, the asymmetry, and the unfinished (and even the broken, the shattered, and the reassembled) are very useful for the aesthetical enjoyment of the world around us. This is a world that is continually changing its "perfect" state. In fact, Japanese culture, more than in the West, has always appreciated and valorized "imperfect" artifacts. The fundamental reason is traced to this culture's aesthetical vision of the world, based on the acceptance of transience: the Wabi Sabi philosophy. This traditional aesthetic approach emerged in 900 AD and peaked in the sixteenth century. It represents the concept of imperfect, temporary, and incomplete beauty. The main features of Wabi Sabi aesthetics include asymmetry, asperity (roughness or irregularity), simplicity, austerity, modesty, intimacy, and appreciation of the ingenuous integrity of natural objects and processes (Juniper, 2003). "Wabi" identifies the rustic simplicity, the freshness or the silence. It can also refer to quirks or defects generated in the process of construction, which add uniqueness and elegance to the object. "Sabi" is beauty or serenity that accompanies aging, when the life of the object and its impermanence are highlighted by the patina and the wear, or any visible repairs. Wabi Sabi suggests feelings of both desolation and loneliness (Juniper, 2003; Koren, 2008; Sartwell, 2006).

Giving value to the imperfect condition, as suggested by Wabi Sabi, leads to a reconsideration of the relationship that one has with everyday objects because imperfections can be endearing and help to create a bond with the user (van Hinte, 1997). The relationship with these objects, whose surfaces and materials have a new aesthetic (compared with when "new"), based on the defect and its associated imperfection, provides a new interaction. This interaction has been termed "fuzzy interaction" (Chapman, 2005) because it is based on the unpredictability of interaction scenarios as opposed to the otherwise traditional. The imperfection, in other words, can also make users' experiences richer and more enduring.

In contemporary design, we can find many approaches that have pointed out, consciously or not, the value of imperfection. Some scholars have recently focused on the gathering of various design approaches through which it is possible to enhance or highlight imperfection (Ostuzzi et al., 2011a,b,c; Salvia et al., 2010). Their purpose has been to highlight ways in which design can exploit flaws, disorders, asymmetries, irregularities, and the lack of balance, which in the end will give birth to objects triggering their users to view those objects as part of a uniform and harmonious natural system. Ostuzzi et al. (2011b) adopted the term "Standard Unique" from Maarten Baas' "Standard Unique Chair", with which they show three main elements to be considered in order to create imperfection and uniqueness in mass-produced objects: the materials, the manufacturing process, and the assembly.

Materials embodied in products have the potential to generate evident aesthetic differentiations especially when they derive from natural raw resources, such as wood and stone (e.g., highlighting wood cracks in the "Stitched Table" by Uhuru Design, 2010; leaving very rough surfaces in marble "Delaware Bluestone" chairs by Max Lamb, 2008). If the materials derive from recycled resources, there is also a high possibility to create unique aesthetic qualities because often they have nonhomogenous structure with various colors or inclusions (e.g., recycled paper in the "Parupu" children's chair by Claesson Koivisto Rune for Sodra, 2009; plastics with inclusions in the "EcoFish" chair by Satyendra Pakhalé for Cappellini, 2010). Similarly, if the materials originate from reused objects or are derived from unpredictable applications, such as processing scraps (e.g., leather scraps in the "Free Seams" armchair by Silviya Dimitrova and Marcello Bonvini for Baxter, 2009) (Figure 11.1) or discarded objects (e.g., various objects in the "Fossili Moderni" range by Massimiliano Adami, 2009), they offer unexpected textual and visual experiences.

The manufacturing process is another factor route through which it is possible to create imperfect but unique products. In every industrial process, there occur anomalies by accident. When this is deliberately sought, and the parameters set for the purpose of creating design defects, designers may create unique objects as a result of an industrial process (e.g., human and process interferences in "Saving/Space/Vase" by JoeVelluto for Plust, 2009; "Roughly Drawn RD4" chairs designed by Richard G. Liddle and manufactured by Cohda, 2007 (Figure 11.2); "Endless" armchair by Gaetano Pesce for Meritalia, 2010; the sand-casted "Hexagonal Pewter Stool" by Max Lamb, 2008).

Uniqueness can also be achieved in the product assembly stage, through a random mounting of modular pieces by the operator or the user, to obtain high degrees of product variation. Recently, an exponential rise in customized, self-assembled mass manufactured products has been observed, especially possessing very distinctive appearance made possible by variations in modular pieces, for example, in the "Standard/Unique" chair (Figure 11.3) by Maarten Baas for Established & Sons (2009) or the "Clouds" modules by Ronan & Erwan Bouroullec for Kvadrat (2006). Modular pieces have always been a key feature for successful customization in industrial production, from kitchen systems to car interiors and exteriors, and are generally characterized by meeting people's needs in a more effective manner and thereby increasing the likelihood of greater longevity.

In the examples listed above, we have seen how imperfection—whether delivered randomly or through purpose—can become an important design resource to create unique products, whose relationship with the user can last over time, fulfilling both functional and aesthetical durability.

FIGURE 11.1
"Free Seams" armchair by Silviya Dimitrova and Marcello Bonvini for Baxter, 2009.

FIGURE 11.2
"Roughly Drawn RD4" chairs designed by Richard G. Liddle and manufactured by Cohda, 2007 (Manufacturing of the Roughly Drawn Chair: https://vimeo.com/7598260).

AGING > IMPERFECTION > UNIQUENESS

Time is a fascinating element that is able to create imperfections and defects in materials resulting in unique objects, which carry traces of life and living. Time has a dual nature: it is the irreplaceable engine of life cycles in continuous transformation, yet it inexorably passes, leaving traces of its passage, deteriorating and ruining. In the arts, the power of time comes into play when the work of man is finished. For example, the day on which a statue is completed marks the beginning of that statue's life (Yourcenar, 1983). Time manipulates it, creates new patterns and shapes it. Just like living beings mature and get older, so too artifacts degrade and their surfaces show signs of aging, defects, and imperfections. Objects have capability to record their experiences, to look back upon the captured records and reconfigure the recordings in order to replay what actually happened (Lee Hyun-Yeul, 2007).

FIGURE 11.3
The “Standard/Unique” chair by Maarten Baas for Established & Sons (2009).

As mentioned in the previous section, the Western aesthetic model is not able to happily welcome imperfections, even those due to the passage of time resulting in aging and degradation. The West especially embraces the idea that a bright, shiny surface contributes to the appeal of a product because the idea of novelty, beauty, and something being fully functional is associated with these aesthetic features, not with marks, imperfections, and stains, which usually accompany aging of a surface. The newness concept of the West is “… a complex mix of sensory characteristics which include the particular odour of new materials, surface integrity, precision of fit/location, colour purity, intentional sound integrity/lack of unintentional sound, tactile integrity (surface consistency, cleanliness) and lack of visible wear. In this context some materials, objects and forms are more forgiving of age than others. For example ‘natural’ materials frequently exhibit beneficial effects of aging and are often homogenous (e.g. polished or unpolished solids) as opposed to those which are non-homogenous and age less gracefully (e.g. laminates and painted surfaces)” (Woolley, 2003). We should comprehend that the idea of newness induces the rapid obsolescence of the product after a short period of use (Walker, 2009), which is also emphasized in literature as “aesthetic obsolescence” (Burns, 2010).

No matter what its shape or material, it is inevitable that any surface in time will gradually lose its initial qualities. In fact, the chemical—physical properties of the material, as well as the environmental stress and its use, lead the surface of a material through an inexorable decline. In engineering, aging is defined as the gradual irreversible changes in structure of a material that occur as a result of the passage of time (De Vreugd, 2011). A material’s aging depends on the nature of the material itself and the operating conditions. Some materials “degrade” while others “mature” by maintaining or improving certain qualities. The positive term of maturity is usually used for natural materials such as stone, paper, wood, and leather, which over the years can acquire scents, colors, and textures: characteristics that far from diminishing their quality, instead acquire an aura of antiquity and preciousness. As van Hinte states

(1997), many natural materials were once alive; they have already naturally aged and are therefore in possession of an innate ability to deal with time. There are objects made of natural materials, such as wood, that through the process of aging, acquire value. A chest, a wooden floor, a wooden table, for example, becomes more valuable and aesthetically pleasing when it is used and has aged. There are also materials that seem inert to the passage of time such as ceramics or that age less well than others such as certain types of plastic. We do seem to share consistent responses concerning which materials "age well" or not (Saito, 2007).

> Concrete becomes more ugly every passing year, looking greasy if smooth, squalid if rough; glass-fibre decays more disagreeably than stonework… Much corrosion – rust on iron, tarnish on silver, white crust on lead and tin – is normally odious; only to copper and bronze does a time-introduced oxidized surface add the luster of a noble patina.
>
> **(Lowenthal cited by Saito, 2007)**

The term "patina" is used today in a broad sense, denoting all processes connected with the aging of surfaces of artifacts with the passage of time, such as a tarnish on a copper surface occurring by oxidation, or a sheen on wooden furniture. The patina often accompanies the maturation of certain materials, especially natural materials, making them also aesthetically appealing (Candy et al., 2008). In Manzini's words (1986), contemporary "ephemeral, transient and instantaneous" materials, represented so well by synthetic polymers, degrade without dignity. For this reason, such materials reach a level of unacceptable degradation because they are not able to respond, above all, to the aesthetic requirements (Fisher, 2004). At that point of time they are discarded. The quality of material surfaces thus acquires also a cultural dimension (yet unexplored) on aging, an ability (or not) to stand the test of time by recording transitory signs with (or without) losing value to people (Manzini, 1986, 1990). Papanek stated (1995) that the environmentally and socially orientated design of the twenty-first century has to include "graceful aging" as the first fundamental principle, since materials that have aged well hold great appeal.

CONCLUSIONS

> Why should this propensity to seek beauty in darkness be so strong only in Orientals? The West too has known a time when there was no electricity, gas, or petroleum, yet so far as I know the West has never been disposed to delight in shadows. Japanese ghosts have traditionally no feet; Western ghosts have feet, but are transparent. As even this trifle suggests, pitch darkness has always occupied our fantasies, while in the West even ghosts are clear as glass. This is true too of our household implements: we prefer colours compounded of darkness, they prefer the colours of sunlight. And of silverware and copperware: we love them for the burnish and patina, which they consider unclean, insanitary, and polish to a glittering brilliance. (…) As a general matter we find it hard to be really at home with things that shine and glitter. (…) Yet for better or for worse we do love things that bear the marks of grime, soot, and weather, and we love the colours and the sheen that call to mind the past that made them.
>
> **(Tanizaki, 1977)**

In this chapter, we have elaborated on an approach for achieving positively experienced "aesthetics of sustainability", based on imperfection and graceful aging of materials. We propose that its consideration can lead to create unique, aesthetically pleasing products that can elicit long-term user attachment. Contemporary materials generally tend to prevent all forms of change in time and acquisition of signs of aging. In other words, they resist as much as possible to become imperfect. In response, we do not suggest that everything must and will be made of leather or wood, but it seems obvious that these materials can teach something that can be applied when developing new materials. The most important suggestion here is to see "aging and imperfection" as a valuable means to create "unique", "personal", and "durable" products. This approach can even be enhanced if the material/product function improves as the result of the passage of time. Think about a Moka pot, for example. A new Moka with perfect aesthetic qualities does not make a good cup of coffee; its function improves over time. A similar example can be found both in Britain and China, where it is believed that one should never clean the inside of an old teapot as the internal tea stains contribute positively to the tea making process.

It is important to emphasize that a designer should not underestimate the opportunity that might come through imperfection—through production, material type, or aging—resulting in a unique and broader definition and range of beauty in products. In relation to that, awareness about the longevity of products is spreading in the world of design production and consumption: an awareness that products must not be designed for "use and throw", but they must endure for the functional and emotional roles that designers established for them. An old product, a unique imperfect product, creates "thought", activates "imagination", and stimulates "curiosity".

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CHAPTER 12

Conception and Realization of a Sustainable Materials Library

Jakki Dehn
Rematerialise, Kingston University

CONTENTS

Designers have an enduring fascination with materials. Their vivid imaginations are fueled by visual and tactile stimuli. They are excited by the mastery of new processes and applications. To designers, materials can be inspirational, offering possibilities for experimental form making, which in turn can create new branding, marketing, and business opportunities. But unless designers understand the environmental impact of the materials that they choose to work with, these opportunities cannot, ultimately, be sustained.

"Sustainable design" is certainly not a new phenomenon. In Vienna in 1859, Michael Thonet devised a method of producing furniture by bending solid wood, resulting in a product that parallels many of the environmental concerns that we have today. Sustainably grown beech wood, steam bent into component parts, enabled mass production of furniture for the first time. Anticipating IKEA by almost 100 years, a minimal amount of material could be used to create a strong structure, components could be flat packed making transportation more efficient, and the product could be assembled upon arrival

Materials Experience. http://dx.doi.org/10.1016/B978-0-08-099359-1.00012-6

at its destination. Chair no.14 was one of the most successful industrial products of the nineteenth century selling millions of pieces worldwide.

The purpose of this chapter is to disseminate the author's experiences in this area, combining a concern for designers' material information and inspiration needs with the prevailing demands of "design for sustainability". It reflects a nearly 20-year personal journey culminating in the ideation and realization of a materials library and resource center.

THE FORMATIVE YEARS

In the 1980s, as a furniture designer in the east end of London, the author was engaged in daily designing-and-making activities that drew upon a network of local expertise and resources. In retrospect, it is clear that the working practices in those days were relatively environmentally sound. Furniture was made to order and nearly every process or material was sourced within walking distance. Wood turners, pattern makers, metal spinners, veneer suppliers and cutters, tool shops, and timber merchants were all in the neighborhood, and some staff would push materials to the authors' workshop door using a hand cart. Reflecting upon design practices a decade later, in the early 1990s, there was a strong concern emerging about the accelerating consumption of natural resources and the amount of waste that products were generating. One day in the workshop, a small box of recycled material samples arrived from Seattle. It was sent by Barbara Johnson by way of introduction to the first Design Resource Awards competition, to be organized in the United States, with the aim of changing attitudes and opening up designers to the challenge of recycled materials. Inside were some extraordinary material samples (Figure 12.1(a)–(d)). These material samples were at an early stage of their development. Designers' preconceptions about recycled materials were reportedly restricting the uptake of the materials in new product designs. "They were thinking: this is a recycled paper, what could I do with recycled paper? Instead of thinking: here's a material that looks like granite, what could I do with granite?" (Johnson, 2005).

The small boxes of material samples united students and professional designers alike in an exploration of new ideas and gave an impetus to the author's own ideas toward creating an organized collection of sustainable material samples that could serve the needs of the design community. Another sample in the competition boxes was a small square of recycled, high-density polyethylene (HDPE), produced by Yemm and Hart in the United States. It captured the attention of British furniture designer Jane Atfield and inspired collaboration with materials scientist and plastics expert Colin Williamson to develop the company, "Made of Waste" to manufacture recycled plastic board in the United Kingdom. Jane's role included promotion for the new classes of materials that they were producing, as well as using those materials in her own design practice.

Atfield, inspired by the uncompromising simplicity of Gerrit Rietveld's chairs in the 1930s, designed the RCP2 using compression-molded, postconsumer, recycled HDPE sheet (Figure 12.2). By producing a simple form in a new material, she hoped that people would notice the material rather than the design. Her chair caught a mood and had a formative impact on designers' perceptions of recycled materials. Rather than dismissing "recycled" as lesser quality, designers were now excited by new aesthetic possibilities.

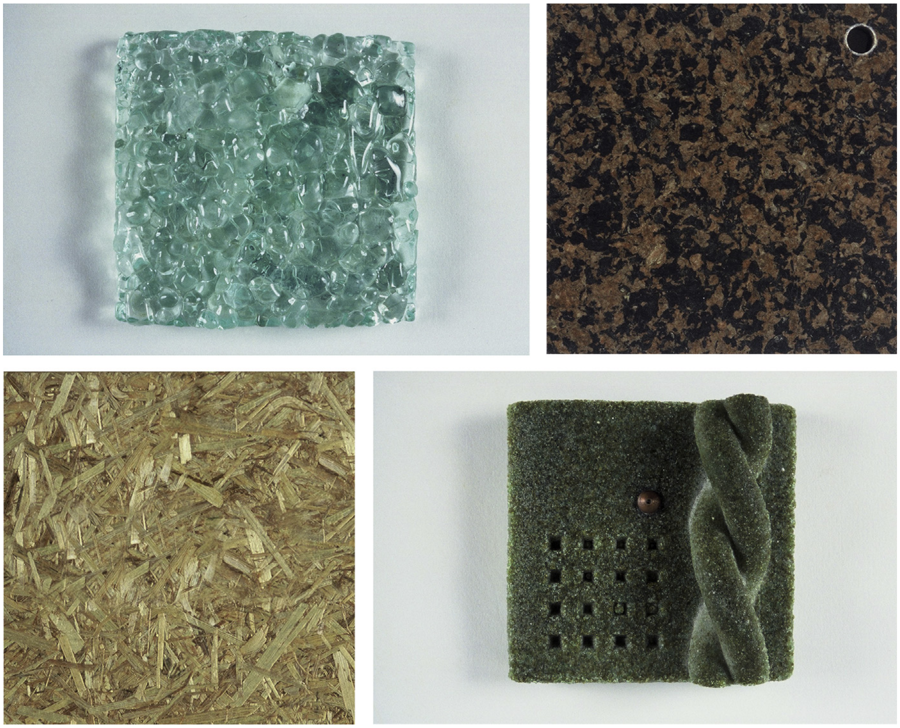

FIGURE 12.1

Recycled materials from the first Design Resource Awards, clockwise from top left: Bedrock Industries, transparent and bubbly glass tiles; Environ, a board made from a mix of waste paper and soya flour that looked like granite; New Design, recycled glass molded to look like an opaque sandy plait; Meadowood, compressed board made from the straw left over from the rye harvest by a farmer in Oregon.

Research into design and sustainable development of materials

In 2003, the Arts and Humanities Research Council in the United Kingdom funded 3 years of research into the sustainable development of materials and the design process. Based at Kingston University, it provided the author with the opportunity to investigate from a design perspective the aesthetic, economic, and manufacturing potential of materials made from waste. Consultations were made with government organizations at a local and national level to explore the potential links between designers, the business community, the regional government, and the waste management industry. Some of the questions driving the research were as follows: Why is there a persistent negative perception from designers, manufacturers, and end users toward recycled materials? How can materials transition from worthless to desirable through designerly manipulation? Could materials made from waste affect the aesthetics of design in a similar way to the impact the use of metal had on furniture in the early twentieth century?

The author adopted the position of Dougherty (2005), who had worked with the UK government organization Waste Resources Action Programme (WRAP) to develop markets for the United Kingdom's increasing volume of recyclate: "it's not a matter about treating waste; to me it's a

FIGURE 12.2
RCP2 chairs designed by Jane Atfield. © *Jane Atfield.*

very serious matter about efficient use of materials". WRAP investigated the idea of waste incineration as a more effective way to process waste, but after extensive work on the life cycle analysis of materials, they concluded that recycling was a more efficient use of waste material (Price, 2006).

Through the analysis of product case studies, it became clear that the force of the designer seemed to play a significant part in the reappraisal of unconventional materials. For example, the "Hudson" bar stool is made from recycled aluminum. It looks no different from virgin aluminum but the designer's involvement transformed the value of the original material from discarded drinks cans to desirable furniture.

In 2007, the "Nobody" chair produced an entirely different aesthetic using technology from the automotive industry (Figure 12.3). Made from two layers of thermopressed felt derived from recycled polyethylene terephthalate drink bottles, it is molded in one piece, in a single process. This simple, lightweight stackable chair has a warm, tactile surface quite unlike the rubbish that it was made from.

Products such as these and the case studies of their development were gathered by 2007 into a collection at Kingston University that became the foundation of the "Rematerialise library". At that time, the resource achieved a sufficient range of materials and example products so as to interest the design community. To reach out to that community, the library was transformed into a touring exhibition (Baxter, 2006) entitled "Creative Resource" (Figure 12.4).

Through material samples and products created from those materials, the exhibition explored the value placed upon materials, the status assigned to recycled materials, and how design innovation can

FIGURE 12.3
"Hudson" bar stool, designed in 2000 by Philippe Starck for Emeco (left) and "Nobody" chair, designed by Boris Berlin of Komplot Design in Denmark (right).

FIGURE 12.4
Excerpt on "rubber" from the Creative Resource exhibition. © *P. Vile.*

transform our perception of waste. Created with designers in mind it was, however, important that everyone could access the information, so that the general public could see that their own recycling efforts had value in the context of sustainable consumption.

HANDS-ON CONTACT: THE VALUE OF A PHYSICAL RESOURCE

In the early days of the Rematerialise collection, many of the materials looked and smelt like the waste that they were made from. It was hard to imagine how they could be used commercially. By 2009, when Kingston University gave the Rematerialise Sustainable Materials Library a permanent home, the situation had changed. Materials had become more sophisticated in appearance and performance and most of them were in production, complete with the technical testing requirements that enabled them to be considered analytically within a materials selection process. Presently, the library houses over 1200 samples of many different origins, from banana tree fibers and sunflower seed husks to scallop shells and denim jeans. The central educational principle of the library is that it offers a hands-on experience aimed at exciting students with the aesthetic and tactile potential of materials considered to have improved sustainability credentials over many more commonplace alternatives.

The possibility to give to students and professionals access to samples and information on a variety of materials and technologies had been raised earlier. For example, in 1997, George Beylerian founded Material ConneXion in the United States. He realized that the creative industries had a need for efficient access to a rapidly developing range of new materials in a tangible form. In 1998, Els Zijlstra started the Materia library in the Netherlands. She found it hard to find information about materials and techniques and felt that it was vital that both the design industry and students had more easy access to material opportunities (Zijlstra, 2005). Among existing material libraries, we can say that Rematerialise was one of the first topical material libraries, focusing on the central concern of sustainability and its impact on material choices.

Materials selection

The word “sustainable” now covers a broad and complex field that it ascribed multiple meanings. To some people there is no such thing as a sustainable material, instead it is the use of a material that introduces a sustainable advantage (Thackara, 2009). For others, supply and manufacture are both important aspects of a material’s environmental impact (McDonough and Braungart, 2002). Although a life cycle analysis of a material would give a better indication of its sustainability, this was evaluated as too time consuming to be realized as part of the information supply available within the Rematerialise library. However, for the library to be of real value to design practitioners and manufacturers, it was necessary to establish some ground rules and definitions to make materials selection and evaluation workable and worthwhile. Three categories of material were defined that candidate materials should potentially fall into before they are selected for the library. The categories are (1) materials that use fewer nonrenewable resources, (2) materials that are easily renewed, and (3) materials that have been overlooked. These categories describe a more efficient use of material content, with a reduced use of finite resources and a better use of renewable resources.

Beyond these categories, candidate materials were required to have a strong aesthetic appeal and be in production, or at least have the potential to generate new business should they switch from a development material to a production material.

The library’s policy is to publicize the existence of these materials, including those still in development, and introduce them to people who may use them. A central belief is that by increasing demand from new markets, opportunities for further environmental improvements will be generated. Material examples from each of the three categories are now presented for illustration purposes.

FIGURE 12.5
Gridcore, recycled cardboard (left) and UrbnRok, recycled glass and shell, UK (right).

Materials that use fewer nonrenewable resources

These are materials that have up to 100% recycled content, many of which can be recycled again.

Gridcore is a honeycomb-structured board, molded from 100% recycled, postconsumer cardboard. It is strong, lightweight, waterproof, fireproof, efficient to transport, can be built up to different thicknesses, and is 100% recyclable. Current applications include factory ceilings, earthquake protection of buildings, packaging, and displays (http://www.pixelwindow.com/gridcore/index.html). GlassEco produces UrbnRok, made from 89% recycled pre- and post-consumer bottles, reject mirrors and sheet glass and cockle shells from the fish industry (Figure 12.5). The glass is washed by hand before use to reduce the use of water and heat. The dust produced from crushing the glass is mixed back into the resin. The sheet can be used for interior surfaces including kitchens and bathrooms (http://www.glasseco.co.uk).

Materials that are easily renewed

These are materials that can be regrown, many of which also naturally biodegrade.

Green Cell is a biodegradable, cornstarch-based cellular foam produced by BioViron (Figure 12.6). It has anisotropic properties, resulting in different cushioning properties in different directions. This provides an advantage that blocking, bracing and shock/vibration protection can be provided through just this one material. It biodegrades in 7–10 days in freshwater and saltwater (http://www.greencellfoam.com/). Zelfo sheet is made from natural materials including hemp, timber, reed, straw, miscanthus, sugarcane, sisal, and jute. The high carbon absorption rate of these plants makes a positive contribution to the reduction of the greenhouse effect. This sheet can include various wastes and recycled materials with high cellulose content. Zelfo can also be pressed into a three-dimensional form with the potential for use in furniture and musical instruments (http://www.zelfo-technology.com/faq/).

Materials that have been overlooked

These are materials that have been developed from waste streams that are not readily collected but have been recognized as a valuable resource.

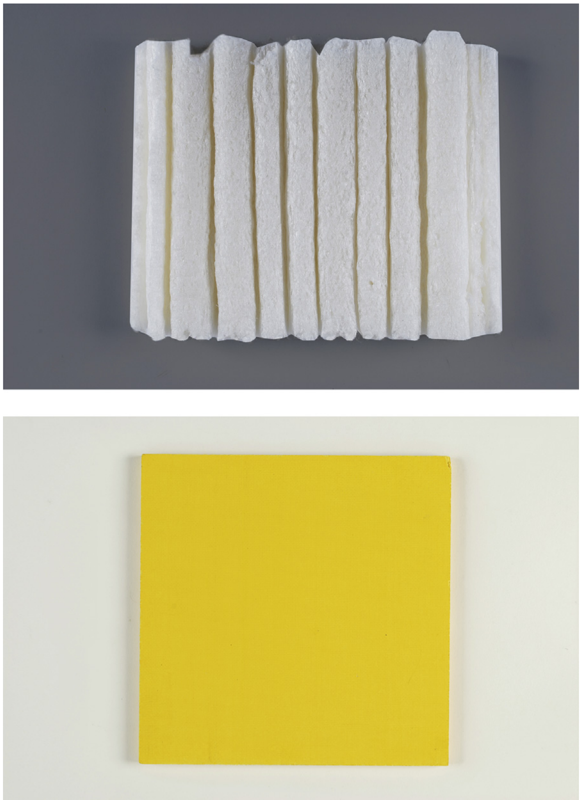

FIGURE 12.6
Greencell, cornstarch, Bioviron, USA (top) and Zelfo, hemp, timber, reed, straw, miscanthus, sugarcane, sisal and jute, Germany (bottom).

The Japanese scallop farming industry disposes of over 200,000 tons of shells a year (Koyama et al., 2003). Aimori Eco Products produce a plaster made from 95% postindustrial scallop shells, with 5% cellulose fiber, carboxymethylcellulose, and color pigments (Figure 12.7). The plaster can be applied directly onto a dry wall and, unlike conventional plaster, does not shrink over time and is not susceptible to cracking. Once dry, it provides a strong, hard, and breathable finish, which helps to maintain optimum moisture levels in a room (http://www.aimori.net/en/products.html). Atlantic Leather produce leather made from 100% recycled fish skin, a food-processing by-product. The fish stocks used are well managed and robust. Renewable energy is used in the production processes; electricity from hydroelectric power and geothermal hot water for the tanning and coloring. The leather is used for fashion accessories including shoes and handbags for brands such as Prada, Dior, and Nike (http://www.atlanticleather.is/).

CASE STUDIES: THE IMPORTANCE OF COLLABORATION

The Rematerialise Sustainable Materials Library is more than a collection of samples. Case studies highlighting the enduring optimism that drives designers to take risks and try things out are another

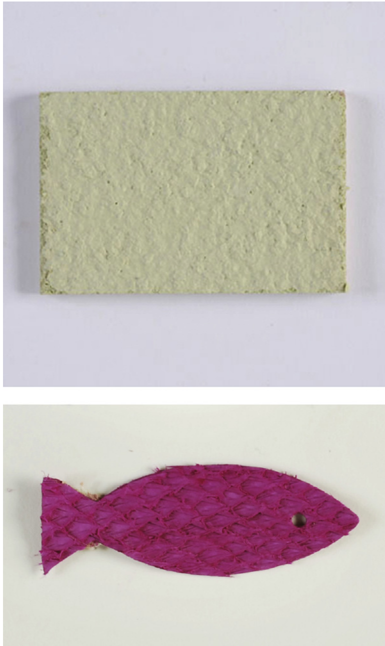

FIGURE 12.7
Aimori Koubou wall plaster, recycled scallop shells, Japan (top) and Atlantic leather, recycled salmon fish skin, Iceland (bottom).

asset that design practitioners can call on. These case studies, drawn from interviews conducted with designers and manufacturers from Europe and Asia, describe how design companies have collaborated with manufacturers to test the significance of environmental concerns as a stimulus for design innovation and commercial success. The results have produced unexpected benefits for the environment. Some examples of the case studies are now presented (Figure 12.8).

Jedco (recycled plastic and recycled glass fiber, United Kingdom)

In 1997, John Elson, Director of United Kingdom-based product design consultancy Jedco, was approached by a group of entrepreneurs to develop a plastic scaffolding board. Elson knew of the materials collection through his work with Kingston University and decided to investigate the use of recycled materials. In collaboration with the plastics industry, it became clear that the majority of the board he wanted to make could be produced from a mixture of recycled polyethylene reinforced with recycled glass fiber. The main impetus was not environmental but economic; Elson found that it would cost less to manufacture a board with recycled materials (Elson, 2004). The resulting board has many advantages over the traditional wooden board. For example, it is 20% lighter and unaffected by wet conditions, enabling more efficient transportation, faster erection, and dismantling. It has no splinters, sharp edges, warping, or knots. The surface is safe, nonslip, dust free, and good for use in sensitive interior environments, having greater resistance to salt water, oil, solvents, and acids. As a material, it lasts three times as long as common alternatives but demands lower maintenance. The material can be

FIGURE 12.8
Clockwise from top left: scaffolding plank, recycled polyethylene, and recycled glass fiber, designed by Jedco, manufactured by Tilon Composites, South Wales; S.A.M Beleaf veneer from banana plant branches, produced by S.a.m. Tout Bois, Monaco; Re-shokki Olivia Tableware, recycled ceramics, designed by Prue Venables produced by Yamama China Co. Ltd, Japan.

color coded and have company names for added security. It conforms to all European platform-loading standards and is 100% recyclable at the end of its life.

Gifu Prefecture (recycled ceramics, Japan)

The ceramics industry, largely based in the Mino district of Japan, is a major part of the country's economy and a significant consumer of natural resources. It was estimated that approximately 140,000 tons of postindustrial and postconsumer tableware was discarded each year in Japan (Hasegawa, 2011). This prompted 30 Mino companies to collaborate on an investigation into the reduction of the negative environmental impact of ceramic production by using recycled ceramics. They began their research by talking to end users before embarking upon new product development. The companies discovered that people had a sentimental attachment to broken china. They did not want to throw these pieces away and would be happy to send them away to be recycled.

After much testing, it was found that not only could up to 50% of recycled ceramics be added to new clay, but that the inclusion of recycled content enabled the firing temperature to be significantly reduced, which in turn reduced fuel consumption. Once the material had been developed, the companies went back to the consumers to engage them with the qualities of this new medium. They sold recycled clay in small quantities and ran workshops for the public so that they could experience the material at first hand. The Mino Ware production companies now share the manufacturing and marketing processes involved in recycling ceramics. They feel that cultivating ties between people in the community through tableware recycling activities is an important part of creating a sustainable society.

Beleaf (banana fiber veneer, Monaco)

S.A.M. Beleaf based in Monaco has developed Beleaf (Biological Engineered Leaf), a range of veneers from the branches of banana plants, which has many uses including flooring, furniture, and joinery.

A banana tree is a perennial herb. After flowering and setting fruit, the branch dies back allowing it to produce a second crop in as little as six months. These fibrous branches, which can grow as tall as 7 m, are then normally left to rot, releasing a huge amount of methane into the atmosphere. Harvesting these branches can reduce greenhouse gas emissions by 58%. The banana plant has a naturally occurring resin, which enables the fibers to be bonded together without the need of chemical additives. Manufacturing requires very little energy and takes place at source. S.A.M. Beleaf works with small landowners under family-based management. This collaborative project has the potential to create a sustainable industry in developing countries across the tropics, with access to a worldwide market.

SUSTAINABLE MATERIALS INSPIRATION AND CONSULTANCY

Nearly all the interviewees who contributed to the research phase of the Creative Resource exhibition (and hence the early establishment of the Rematerialise library) had involvement with design education and were convinced that facilitating student interaction with emerging designers—or more likely their designs—was an important part of their work to promote sustainable values. Professor Fumikazu Masuda, director of the design consultancy OpenHouse and one of the participating interviewees, was an early practitioner of ecodesign in Tokyo. He teaches at Tokyo Zokei University and is careful to involve his students with his work. A few years ago, OpenHouse bought a rice field and twice a year Professor Masuda goes with his work force and students to plant and harvest the rice, which is then shared among them. This experience gives everyone involved a direct understanding of how hard the land works to sustain us. Furthermore, personal anecdotes can lead to important self-reflection on the sustainability of our current cultures and habits and on our reliance on materials, as exemplified by Masuda (2005).

> One day I was walking beside a beautiful river in Kyoto and found something just thrown away, just dumped by the river, this beautiful environment, I was upset and soon after I noticed that it was a washing machine I had designed a couple of years ago.

Masuda stated that he was so shocked by this experience that it compelled him to think more about the consequences of design. In the past, traditional Japanese craftsmen knew everything about materials; in Masuda's opinion, he feels it essential for designers to go back to the earlier generations' understanding of materials.

Recent collaborations between academia and industry have demonstrated the benefits of materials consultancy focusing on the sustainability agenda. In 2010, the Rematerialise library completed a report for the UK retailer Marks and Spencer on materials derived from reduced nonrenewable resources that could be used for the interior fit-out of their new London headquarters. The collaboration was successful on several levels. The fit-out architects revised their material specification as a result of the environmental benefits that had been demonstrated. Business was generated for manufacturers whose materials were included in the Rematerialise library. The manufacturers' confidence in the library grew concomitantly, such that their new products were submitted for inclusion in the library at an earlier stage of development.

FIGURE 12.9
Sugar Jars developed by Byung Joo Lee, Kingston University, UK.

Today, manufacturers are keen to have their products featured in the library. Marks and Spencer saw beyond the economic value of the work to the value of new approaches and set the Product and Furniture Design students at Kingston University a project to design environmentally responsible public seating for the reception area of the new headquarters. Eight students won substantial prizes and were given work experience in the offices of Marks and Spencer.

In their personal work, Kingston University design students are inspired by the Rematerialise library to try out new avenues of materials and design. First-year students have used the resource to assist their investigations concerning the role that materials have on product desirability. For example, Byung Joo Lee baked a hollow container made from sugar and then turned it on the lathe, creating a very different product experience (Figure 12.9).

The by-product of juice and fruit salad manufacture is a solid fruit waste that has become a major environmental problem. This rich mixture of peel, membranes, and seeds ends up in landfill and can be

FIGURE 12.10
APeel developed by Alkesh Parmar from waste from the orange juice industry, RCA, UK. Copyright Alkesh Parmar.

toxic to animals. In another student project example, Alkesh Parmar, a recent graduate of the Royal College of Art in London, turned solid fruit waste into APeel, a material that can be processed into flexible sheets or rigid solid forms (Figure 12.10). Through his explorations, Parmar is keen to link his design process with a clear ethical agenda to encourage new business opportunities. In the example in Figure 12.10, APeel is used to produce a new product from existing molds, thereby also reducing material consumption in the production process.

CONCLUSION

Supported by the Rematerialise library, environmental awareness has become part of the design ethos at Kingston University and beyond. The handling of samples in the library has the potential to counteract the growing trend of withdrawal from the material experiences of the physical world. The tactile and aesthetic qualities of the material collection have given different disciplines a common focus. The stories behind the materials are as important as the samples themselves, as emphasized by the inclusion of example stories within this chapter. Case studies show that collaboration between designers and manufacturers can lead to positive and sometimes unexpected outcomes with far-reaching benefits. Together, the physical and intellectual strands that the library represents have enabled the loop to be closed between environment, designers, industry, communities, and education. The continued involvement of designers and manufacturers with the Rematerialise Sustainable Materials Library will fuel the virtuous circle of material sustainability, using materials in an environmentally considerate way to design desirable products, generate business, create employment, and sustain communities.

Acknowledgments

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Thanks to the interviewees: Johnson, B. (2005) from Johnson Design Studio Architects, Seattle, USA; Atfield, J. (2004) from Unity Peg, London, UK; Dougherty, D. (2005) the waste management advisor to UK Government, Seattle, USA; Price, J. (2006) the Chief Executive of WRAP, London, UK, Liddle, R. (2005) from CODHA Design, Newcastle, UK; Zijlstra, E. (2005) from Materia, Netherlands; Recycling Action Yorkshire (2007) from Barnsley Design Centre, UK; Thackera, J. (2009) from Kingston University, UK; Elson, J. (2004) from Jedco, Surrey, UK; Hasegawa, Y. (2005) from Gifu Prefectural Ceramics Research Institute, Director of Green Life 21, Japan; Masuda, F. (2005) from Openhouse, Tokyo, Japan.

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CHAPTER 13

Sustainable Multipurpose Materials for Design

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Haute Innovation — Agentur für Material & Technologie

CONTENTS

The world of materials is going through radical changes. Diminishing resources, new energy challenges, and stricter environmental restraints are forcing producers and developers to change their mind-set. Customers increasingly ask for products for which the different aspects of sustainable product and design culture are a top priority. The "sustainability" factor has become a definite commercial selling point. The orientation of our industrial culture is undergoing rapid changes (Peters, 2010).

At the same time, a reorientation of the perceived role of the designer in the innovation process has taken place. The role has gone from "application-oriented implementer to a conceptually deliberating original thinker who, through an active dialogue with manufacturers, fosters the development of new materials or production processes or develops them himself" (Bürdek and Eisele, 2011). "The emphasis turns from the attributes of a material to its performance. Designers engage in the technologizing of materials and proactively determine the material behavior instead of only taking it into account" (Klooster, 2009).

Countless developments support the notion that a real reversal in the classic view of innovation has taken place (Stöck, 2012). Designers no longer just contribute a "postproduction beautification" at the end stage of a technological innovation. They are rather equal partners and an integral part of the development process (Peters, 2007). More and more often, the development of a material and the elaborating of its application no longer take place separately in sequential processes, one after the other, but instead take place simultaneously (Peters, 2011a). In this way, the development of the material is able early on to take into account important information as to the future context of its

Materials Experience. http://dx.doi.org/10.1016/B978-0-08-099359-1.00013-8

application. Also, in accordance with the wishes of numerous innovation researchers, the needs of the marketplace are the focal point of research activity from the very beginning.

The changed view of a designer's role in relation to the growing awareness of the importance of sustainability in design is most evident in the numerous developments in the fields of material and technology that have been implemented in recent years. Examples include bioplastics derived from fish scales, furniture with a surface made of bacterial cellulose, or a car body that was spun by robots. Such developments have become part of the established knowledge in the world of high-tech research. Designers use scientific advances to satisfy the growing need for a product culture that prizes sustainability. Small wonder, then, that most advances have taken place in the fields of biobased materials, innovative lightweight construction solutions, and smarter materials.

BIOBASED MATERIAL DESIGN

Furniture made of popcorn, lamps out of coffee grounds (Raúl Laurí), or throw-away sandals made of palm leaves (Tjeerd Veenhoven): the trend toward biobased solutions is currently spilling over from the supermarket to the creative sector, bringing with it ever more fantastic concepts, much to the delight of the savvy disciples of design. Spurred on by the longing for a clean and ecologically sound world, the modern designer's shopping list is a clear demand aimed at material producers: production should be based on renewable raw materials and products should be recyclable and biodegradable.

The use of organic waste in product production has played an important role in allowing designers to surmount previous boundaries of feasibility. Certainly, one of the most interesting ideas is represented by the work of the Berlin designer Julian Lechner, who, in his "Ex-presso" project (2010), used coffee grounds from an espresso machine as the basic material for the production of cups whereby he bonded the particles with natural binders like casein or bioresins (Figure 13.1). Upon using caramelized sugar as a binder, he made a very interesting discovery: during use, the coffee in such a cup actually served to slowly dissolve it, which had the effect of adding aroma to the drink. The Italian designer Raúl Laurí

FIGURE 13.1
Coffee cup made of coffee grounds by Julian Lechner.

went even one step further by exhibiting at the Milan Furniture Fair the lamp collection "Decafé Lamps", the lampshades of which were made from coffee grounds.

The Dutch designer Mandy den Elzen (http://mandydenelzen.com) has also attracted a lot of attention through the use of unusual organic waste materials. After her project "Algae vase" (2009), in which she transformed algae fibers into containers and vases, she began in 2011 to use waste material from cows like, for example, the cow stomach, in order to create a kind of leather-looking material with an interesting hexagonal honeycomb structure. The material is somewhat transparent and is available under the name "Rumen Leather" in pieces in sizes up to 400 × 500 mm with a thickness starting at 3 mm.

The London designer Erik de Laurens is responsible for one of the most bizarre recent developments. It was based on a discovery he made during a development aid project in a Cape Town township. Mr de Laurens was able to make a material out of fish scales that could be used to produce molded parts like goggle frames and drinking cups by means of applying heat and pressure without the need of a binder (Figure 13.2). In doing so, he made a discovery that could play an important role in the transition from petrobased to biobased chemistry.

In the realm of bioplastic production, the Dutch designer Thomas Vailly has also made a noteworthy contribution (Figure 13.3). For the occasion of the Milan Design Week 2012, he prepared a presentation of a production process for making drinking cups that uses human hair as the fiber material in the production of molded parts. He mixed the hair with glycerin and sodium sulfite, which produced a bioplastic resembling leather that was capable of being formed into all different kinds of shapes. It goes without saying that the material is 100% naturally compostable.

In the search for alternatives to synthetically made materials, producers are meanwhile turning to organic growth processes that are actuated by bacteria, enzymes, or fungi. One of the most famous examples is the production of rigid foam by Ecovative Design in New York that is based on a mycelium fungus network. The cultivation of fungi has in the meantime attracted such a large fan base that even designers have acquired an interest in the new possibilities. The Academy of Media Arts Cologne has installed the project "Fungutopia" as an on-line community in order to promote

FIGURE 13.2
Material made of 100% fish scales by Erik de Laurens.

FIGURE 13.3
"The metabolic factory" by Thomas Vailly.

the know-how necessary for using fungi in medicine or as food or fertilizer. According to the initiators Laura Popplow and Tine Tillmann, fungi are very easy to cultivate and are consequently ideally suited for use as a biomass producer, especially in big cities (http://www.makeandthink.de/fungutopia/).

Cellulose fiber is one of the most important fibers for the textile industry. In recent years, fzmb GmbH, a research center for medical technology and biotechnology, has researched the process by which microbes can "spin" cellulose through fermentation and the way in which gellike textile surfaces with thicknesses up to 4 cm can be organically grown. Compared to plant-based cellulose, bacteria-based cellulose is much thinner. It consists of a high-complexity nanostructure. It contains small constituent elements such as lignin, which make the fibers highly flexible and very stable at the same time. Bacterial cellulose can grow into almost any shape and can be produced on a variety of sugar-containing substrates. Due to its biocompatibility and high purity, bacterial cellulose has found application in the medical/cosmetic fields and was used in the design field by Jannis Huelsen in the Project "Xylinum" to create a special surface on a wooden chair (http://www.skin-futurematerials.com).

With his "FluidSolids", the designer Beat Karrer from Zurich has succeeded in developing a shapeable mass that can be processed using the conventional forming procedures. The base material is made up of industrial by-products from renewable raw materials and holds its eventual shape through the use of protein-based natural binders. In addition to its odor- and emission-free processability, it also requires less energy input than conventional material processing (Figure 13.4).

LIGHTWEIGHT MATERIAL DESIGN

"Spinnenrad mit Hüftschwung" (Spider wheel with Hip Swing) was the title of an article in the magazine *Der Spiegel* that chronicled one of the most unusual competitions found in the Republic of

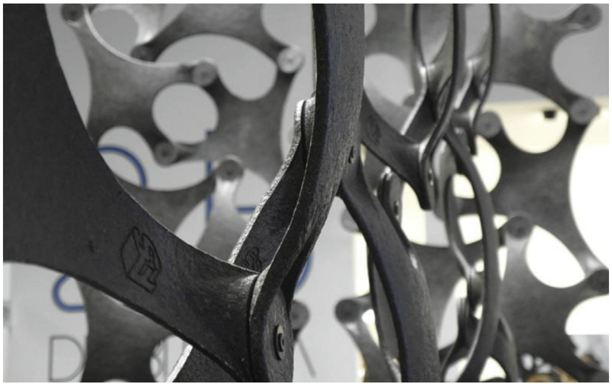

FIGURE 13.4
FluidSolids—molded shapes by Beat Karrer. *In Peters, 2012a.*

Germany: the Cordless Screwdriver Race. In 2011, the seventh edition of this event was held at the HTW Hildesheim (College of Technology and Economics, Hildesheim). Design students from all over Germany and Switzerland were invited to compete against one another in vehicles whose only power source was a standard cordless screwdriver. What at first glance may have looked like a recreational activity, upon closer inspection turned out to be a serious scientific project. This is because it was not only the speed of the vehicles that mattered but rather more specifically the development of unusual solutions to the production of lightweight constructions. The success of electric mobility will depend to a crucial degree on the progress of weight reduction measures in construction elements. High-strength lightweight polymer construction solutions, carbon fiber materials, or bionic constructions using generative technology (three-dimensional printing, laser sintering): every pared down gram of material allows the reduction of the dimensions of the battery and increases the range. These are factors, then, that will be decisive influences on market acceptance of electromobility.

A good example of a material efficient production process for furniture based on a generative design principle comes from the Dutch designer Dirk vander Kooij at the DMY Design Festival in Berlin 2011 (Figure 13.5). He only used shredded plastic waste from refrigerators and a robotic arm. The plastic particles are melted down in a container until a nicely flowing mass is formed. The robotic arm then travels over a path determined by the shape of the desired construction piece, emitting said liquid plastic along the way. As the plastic cools it becomes hard. Layer after layer is added until the furniture (in this case a chair) is completely formed.

The Nanospyder is another designer-initiated project concept for using generative production as a way to increase material efficiency, this time from the Volkswagen Design Studio in California. This entry in the LA Design Challenge displays in an exceedingly impressive manner how innovations in materials and in fabrication techniques will change car construction in the future. The designer's plan consists of billions of tiny nanodevices measuring less than half a millimeter in diameter automatically attaching themselves to one another to form the lightweight construction structure of a new automobile. Thanks to this cumulative and highly flexible fabrication process, the weight, performance, and energy

FIGURE 13.5
Generative furniture production using plastic waste, by Dirk vander Kooij. *In Peters, 2012b.*

efficiency is optimized. Material only expresses itself where it is in fact necessary. In addition, there are intelligent deformable zones that are programmed to anticipate exterior forces and adjust accordingly (crumple zones), thereby providing a high degree of safety.

Designers are also in the business of demanding that classic construction materials be replaced with natural materials that have lightweight construction potential. The US designer Craig Calfee was one of the first to produce a bicycle frame made of bamboo. The advantages of bamboo are numerous: it is a fast growing grass that has enough strength to withstand compressive forces and has special vibration dampening characteristics as well—all of which make it an excellent choice for use as a construction material. This, then, leads to designers turning to a bamboo construction in applications where normally aluminum would have been used, with the further advantage that the bamboo version can be built in a developing country like the Philippines.

By designing a middle layer made out of bamboo cane pieces that are cut at an angle, Wassilij Grod from Conbou has recently come up with a material efficient construction solution called Bambus-Leichtbau-Platte, which is a lightweight bamboo composite board (Figure 13.6). The construction provides a high degree of compressive strength with a reduced amount of material. In addition, by employing ring structures the amount of waste is reduced to a minimum. A further advantage is that by varying the configuration of the core, the firmness of the board can be adjusted for different uses in furniture, trade show, and stage constructions or coachwork. This project was awarded first prize at the European Architecture and Design Competition "ADREAM" in 2010.

The lightweight construction element, a creation by the designer and architect Jens-Hagen Wüstefeld, represents a material-independent, purely constructive way of accomplishing material efficiency

FIGURE 13.6
Bamboo lightweight composite board, by Wassilij Grod.

(http://www.haute-innovation.com/en/magazine/lightweight/lightweight-construction-element.html). The elements consist of a crystal lattice comprising triangles, a structure capable of withstanding introduced forces from all directions and distributing them to the adjoining areas and edges. This structure has enabled a weight reduction of 85% as compared to solid material. Round, spherical, and profiled elements can be made of different materials and directly linked with one another. Any type of material can be used to produce the elements by simply making diagonal cuts in strips of the chosen material and interlocking the strips with one another.

Spiders have populated the earth for about 400 million years and have developed various methods for capturing their prey. One of the most well known is of course the spider web. The fibers and nets produced by spiders in the wild have a unique stability and elasticity. Spider silk, in relation to its extremely fine structure, is as hard as steel and as elastic as rubber. For years, scientists have tried to solve the puzzle of spider silk and to reproduce it industrially. Prof. Thomas Scheibel has finally succeeded. Using a fermentation process that treats genetically modified bacteria, spider silk proteins can be created in unlimited amounts and these can then be spun into a thread material. This new technology prompted the designers at Nissan to develop a futuristic concept car for the LA Design Challenge 2010 (Figure 13.7). The Nissan iV is a super lightweight four seater made from "organic synthetics" that can be cultivated like agriculture. Every detail of the Nissan iV is predicated on sustainability and lightness. Fast-growing ivy reinforced with spider silk forms a flexible, ultralight, and extremely strong biopolymer frame.

SMART MATERIAL DESIGN

Printed photovoltaic elements used as a location-independent electrical power supply to components, surfaces with transformable transparency and color attributes, systems that make it possible to produce individual energy: smart or intelligent material solutions such as these integrate several functions that

FIGURE 13.7
The concept car Nissan iV, by Nissan Design America.

reduce the extra material use and have the effect of stimulating the denizens of the creative world to more and more outstanding advancements and breakthroughs. One great example is "Solid Poetry", a concrete material developed by the Dutch designer Frederik Molenschot that reveals a hidden design or message when it is exposed to rain or moisture (Figure 13.8). The material, which in the meantime has also become known as "Blumenbeton" (flowering concrete), has been furnished with a special coating that reacts to water. In pedestrian zones and public places, this intelligent concrete makes possible a new kind of urbane sign language.

Another interesting development in the construction material sector that was realized by an interdisciplinary team that included an artist, an architect, physicists, and engineers is the product BlingCrete (Figure 13.9). It is based on the optical phenomenon of retroreflection being used as a means of making communicative surfaces on construction materials (Zimmermann, 2012). This is accomplished

FIGURE 13.8
Solid Poetry, by Fredrik Molenschot. *In Peters, 2010.*

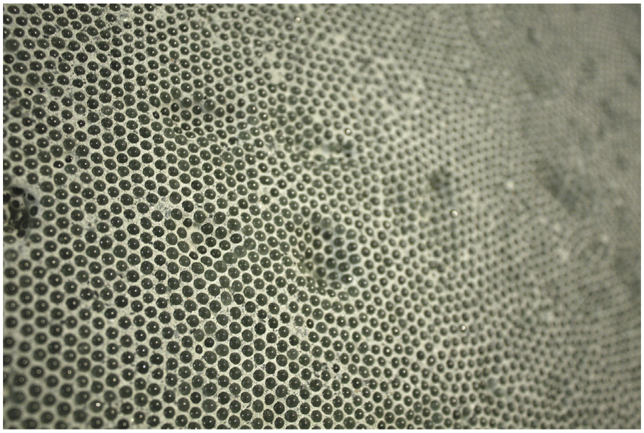

FIGURE 13.9
BlingCrete by Heike Klussman and Thorsten Klooster. *In Peters, 2011c.*

through the integration of micro glass balls in the top layer of the concrete. The result is that incident light is always reflected back in the exact direction from which it came. Based on this principle, things like the edges of platforms, stairs, or sidewalks can be marked out for safety purposes without all the complications involved in the use of electronic components. This results from the fact that if one finds oneself in the focus of the reflection, the glass balls can be clearly seen but from other angles they seem to disappear.

Producing light in an organic way was designer Nicola Bruggraf's big idea. She created an installation with lights that were based on the "bioluminescence" principle and these elements reacted to the movements of the museum's patrons by emitting light. Acting as a kind of organic motion sensor, the installation, which was mounted for the Light + Building tradeshow in Frankfurt, gave the visitors direct feedback, thereby responding to any behavior taking place within the range of operation. And this all without any electricity—which was not needed because the organisms (single-celled algae) produced their energy during the day by means of photosynthetic processes and released it in the evening as light.

Piezoelectricity is a great source of potential advances in the realm of design and product development, especially in the context of small-size energy systems (Ritter, 2006). After Massachusetts Institute of Technology in the United States developed an athletic shoe at the end of the 1990s that was able to produce energy while being used for running, the number of other technological uses designers discovered grew immensely. Probably the most famous of these is the flooring system "Power-Leap", which was developed by the designer Elizabeth Redmond in 2006 at the University of Michigan. Another example is seen in the use of piezoelectricity by Döll Architects in the "Sustainable Dance Club" in Rotterdam (Figure 13.10). The kinetic energy produced by the dancing patrons is transferred through the flooring and used to directly generate the energy required for the lighting of the club and the operation of the spotlights. If, then, the dance floor is empty, the amount of light in the room will decrease accordingly.

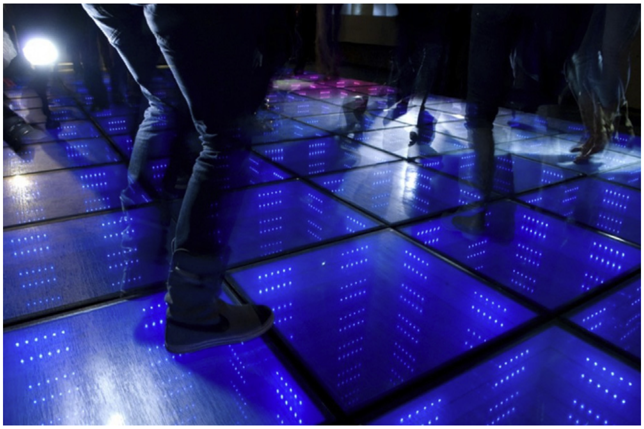

FIGURE 13.10
Sustainable Dance Club, by Döll Architects. *In Peters, 2012b.*

A most interesting irrigation system for the dry regions of the world, which is based on the principle of the hydrophilic skin of the Namibian beetle, was awarded the James Dyson Award in November 2011. The beetle's microscopically small skin structure gives it the capability of "extracting" water from the air; the beetle can thus survive in even the driest desert regions. Dewdrops stick to the skin, gather together on the water-absorbing surface, and drip off onto the thick chitin shell and run down channels into its mouth. The Australian designer Edward Linacre analyzed this phenomenon and transferred the working principle to an irrigation system. Airdrop pumps air through a network of underground pipes to cool it to the point at which the water condenses, thereby extracting the moisture out of the air (Figure 13.11). The water is then distributed to the plants. According to the calculations of the developer, as much as 11.5 ml water can be extracted from a cubic meter of air even in excessively dry areas.

FIGURE 13.11
Airdrop, by Edward Linacre.

CONCLUSION

These examples show how the current design process is more and more concerned with high-tech solutions. The role of designers has changed noticeably in recent years, from that of an application-focused consumer to a conceptually deliberating thought-leader seeking novel possibilities. In addition, designers have now, through all the research on novel materials and new production processes, been provided with options that themselves will prompt even greater changes in the design process in the future. The interdisciplinary dialogues between the research, technologization, and design fields will lead to sustainable product development, with new types of material also playing a more and more important role.

The representatives of the creative industries work together with manufacturers to encourage the development of new materials or manufacturing process or develop them on their own. They thereby transfer the rudimentary achievements of the research sector into a successful application context and are the forerunners of a new material and design culture that is based on sustainability factors. Designers engage in the technologizing of materials and proactively determine the behavior of materials instead of only passively taking it into account. A sustainable product culture is based on interdisciplinary processes among the research, technology, and design sectors.

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Interview with

Paolo Ulian

WHAT ARE THE KEY ASPECTS AFFECTING YOUR MATERIAL CHOICES?

The location is essential. In my projects I have always tried to enhance the local environment. Then the choice must also be consistent with some of my ethical principles. In fact I've always tried to focus on natural, renewable and simple materials. I usually like to work with basic materials, such as terracotta and material made by natural forces such as earth, water and fire. I strongly believe that stone is the material for excellence. I also really love wood and I think it has some features in common with marble. Every time it is different, every piece is unique: the veins are different; the color is different. In contrast, I don't like materials that are too technical, complex and showing their artificiality. Nevertheless I think it is very useful and interesting to be experimenting with new processes and seeing how they can affect the uses and the potentials of traditional materials. For example, water jet cutting opened up for marble an endless array of new capabilities; the material is the same but it creates a world of new solutions and results.

Over the years I also happen to be fascinated by materials with special characteristics, surprising materials that fascinate me beyond their natural and genuine aspects. In fact, in general, these definitions are not clear and mathematical; sometimes some materials with a certain appearance can fascinate me through my senses, causing me to feel warmth and lightness. I can say that there are several factors that influence the choice of materials; I think that you should never preclude in any way but simply follow your instinct.

ARE ANY OF THESE ASPECTS DIFFERENT THAN 10–20 YEARS BACK?

Compared to a few years ago, I have certainly evolved my modality to design, achieved through enriching experiences. I could say the same in relation to materials selection. I focused on things that initially I didn't consider very important, such as aesthetic qualities naturally conveyed by materials. My inclination towards natural materials has not changed, though maybe I have become more conscious. Since I can remember, I have always been inspired by materials with histories; the more ancient they are, the more I like them. Classic materials are a starting point, after which I could look to technology as an element that may give rise to new results.

IF WE SAY 'MATERIALS & SUSTAINABILITY', ... ?

By creating an object and using only a natural material or several natural materials, I hold into account its impact on the world. In today's society I cannot be absolved from thinking to act in a respectful and non-destructive way. If I use complicated and composite materials it would be easy to feel guilty; conversely, when using ceramic, terracotta, marble, or paper I'm definitely more at peace with my conscience.

Moreover, today it is ever more important to think in terms of durability. The designer can no longer afford to use inferior materials just to feed

BIOGRAPHY

Paolo Ulian studied at the I.S.I.A. (Institute of Industrial Arts) of Florence, were he received a diploma in Industrial Design in 1990. At the end of 1990, he started working with Enzo Mari. In 1992, he returned to Tuscany to open his own studio together with his brother Giuseppe. In the following years, he won the "Dedalus" Design Award. Paolo Ulian has collaborated with Droog Design, along with a large portfolio of Italian companies including Fontana Arte, Luminara, Zani e Zani, BBB Bonacina, Sensi&C., Coop, Azzurra Ceramiche, and Skitsch. His second personal exhibition, edited by Enzo Mari, was held at the Triennale di Milano in 2010.

Image Credit: © Luigi di Pasquale,
courtesy of Intramuros

a market based on rampant consumerism; it is necessary to think differently and support the use of authentic and durable materials, they can address more than one life cycle.

WHAT ABOUT 'MATERIALS & TECHNOLOGY' ...?

Technologies, in the sense of new manufacturing processes, can be used to test and investigate but are not part of my daily consideration. Often I try to use classic processes, even archaic ones. As a craftsman, the manual work and the understanding of the limits and potentials of a material through trial and error, through physical contact with things, all of these things have a very important value for me. Through the manual experience you can investigate design territories that otherwise would not have been assessed. To commit an error during the process or to find an imperfection are things that can sometimes open new doors to new perspectives and give birth to new, totally unexpected results. The error has an indispensable value in the design process: I'd say it's almost a part of the project, not something to be avoided. With materials such as smart materials and nanomaterials I do not feel at ease because I cannot understand and see the full picture. I need to fully understand the materials in order to properly interact with their production process. It is often just knowing the production process of a material in depth that can lead to change and to suggest new rules, which can then lead to new applications.

MATERIALS & USER INTERACTION...?

The user interaction is very important in my projects and sometimes, maybe unconsciously, I chose materials that facilitated this interaction. For example, a surface ready to accept the signs of the interaction, as in the top of the stool / table steel frame, which will be characterized over time by the signs of the hammer used to plant the seat in the ground (Pin, 2006). Or, tiles for public spaces designed to facilitate the graffiti style writing seen in public toilets (Tile Page, 2001).

In general I prefer poorly characterized materials, not from a certain expressive point of view, but to be still investigated and designed. The simple and raw semi-finished materials in fact are subject to further characterization by the designer and in my opinion this is where the design of interactions starts. If you use already sensorially characterized materials, the contribution of the designer is minimal. There is little to add and to say.

FROM WHERE DO YOU GET INSPIRATION AND INFORMATION FOR YOUR MATERIAL CHOICES?

My inspiration comes from the preposition that I must go deep into the knowledge of things. This leads me to search for information at the source, directly from the manufacturers. This attitude is often the starting point for my inspiration. I live in Tuscany (Italy), in Massa Carrara, known as the city of marble. This gives me the opportunity to come in touch with this natural material and the manufacturing processes developed in this area. For this reason, the use of marble is a reoccurring theme for me. Sometimes the materials selection comes from discussions with other designers. At other times, my inspiration comes from artifacts and objects that I find randomly and take home because they stimulated my interest, although at the time possibly I do not know exactly how it may be useful. Another method that allows designers to obtain information on materials is the classic fact that a company instructs you to do something with a given material. In this case, you can explore the material and its processes with the strong support of the company. This is the case in the project for the chopping board called Virgola (Zani & Zani, 2001) made of polyethylene. I realized that when a polyethylene sheet was forced manually, you could alter its shape and it would remain so. This observation led me to the creation of a chopping board with handles that rise gently over the ground plane to facilitate gripping.

In the past I have visited some materials libraries but in general I didn't enjoy them and I didn't find them that useful. Yes you can see a lot of materials and some of these are amazing, but in many cases is not possible to understand how they are made and how you can process them. I like to understand how things work and if I don't know where a material comes from, I miss a crucial stage in my design process.

HOW DO YOU THINK MATERIALS SHOULD BE TAUGHT IN DESIGN EDUCATION?

Materials must be taught through contact and use. It is necessary to have a laboratory with materials available from direct experiences. When learning to use materials with a design logic it is useful not to be thinking about what to do with these materials by sitting in your beautiful office, but by looking for direct experiences in the field: by making mistakes, to try and try again, by trial and error and by going in the opposite direction compared with what others have already done. In this way you could find an unconventional yet still feasible answer. By experimenting directly on the material it is possible to access immediately the tactility, texture, warmth, and weight aspects. That is, all the elements that your brain can then easily rework to create new hypotheses. Of course, on an academic level, the technical notions are always important. But once you've experienced the materials directly in your hands you will arrive at the same point. It's like making love or reading about it in the Kama Sutra: it's not the same thing. Existence is based on our five senses, not just one.

Introverso

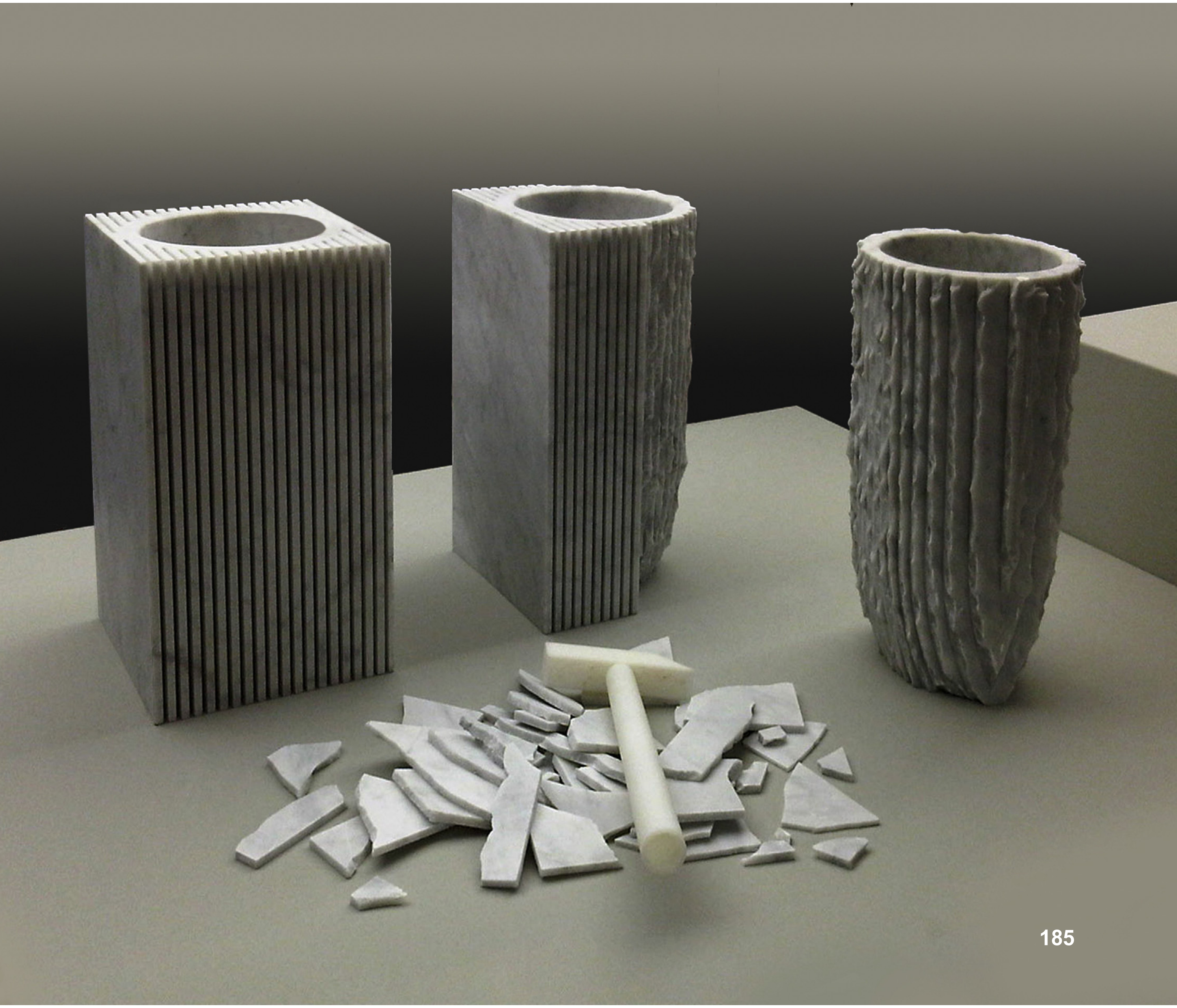
Client: Vallmar (www.valmar.eu)

Year: 2011

Product Material(s): White Carrara marble

Brief Description: It conceals in its same matter another vase of a different form. They are two parallel stories but at the same time independent; the first excludes the second and vice versa. A small hammer (one flower vase) leaves us with the decision to opt for the vase already seen or what is waiting to be released.

Image Credit: © Paolo Ulian



Tavolino Concentrico

Client: numbered edition, Le Fablier (www.lefablier.it)

Year: 2011

Special quadrangular shaped rings are constructed using a water jet technique currently used for working marble. As well as aesthetic guidelines, the design of the form derives from the optimizing of concentric cuts on the square surface of the marble, so as not to waste any material. The rings are then put together and overlapped and the resulting modules are combined to create large surfaces. Modules measuring 60x60 can be freely put together to create compositions as desired.

Image Credit: Modular coffee table made of white Carrara marble. © Gionata Xerra

Virgola Bread Board

Client: Zani&Zani (www.zaniezani.it)

Year: 2001

Product Material(s): Food-grade polyethylene

Brief Description: This breadboard is characterized by a great handle that is raised from the plain surface, allowing easy handling. The handle is raised after cutting and mechanically retains the raised position thanks to the particular characteristics of the material from which it is made.

Image credit: © Paolo Ulian

Cardboard Vase

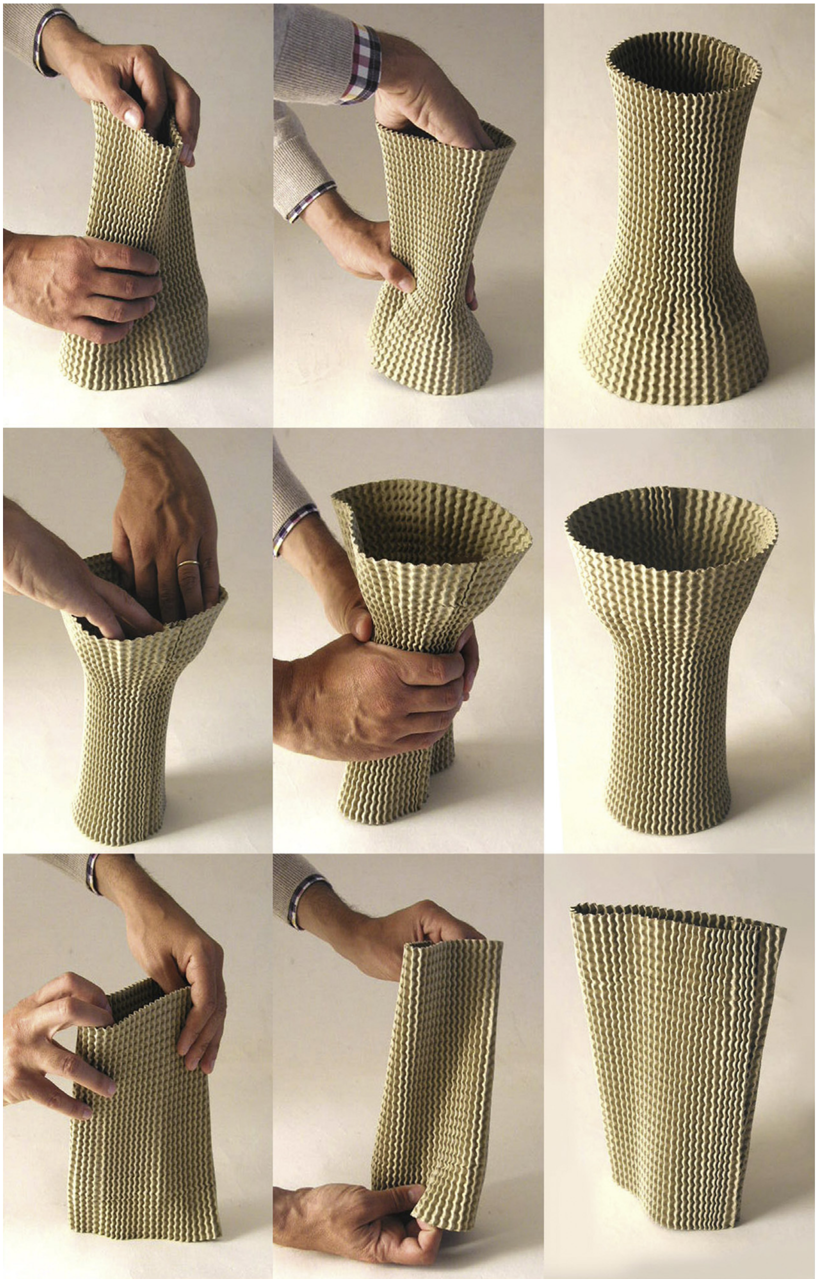
Client: Edizioni Corraini (www.corraini.com)

Year: 2012

Product Material(s): Elastic cardboard

Brief Description: These vases, whose shape is the result of manual modeling of corrugated cardboard tubes, are usually used to pack bottles and jars. The vase can be shaped into an endless variety of forms before being painted or left neutral. The vase provides a unique and eco-friendly solution for homes.

Image Credit: © Paolo Ulian



Interview with

Piet Hein Eek

WHAT ARE THE KEY ASPECTS AFFECTING YOUR MATERIAL CHOICES?

If there is a material with which I will not be able to do anything- cast iron for instance- I don't choose it. But if I know somebody who has a machine to process it, I start looking for the possibilities. It should simply be easy to realize it! I don't put energy into a new material or a new technique, which is not easily accessible. Thus the material I choose must firstly fit in with the existing machines that I have; or at least I should be able to reach or know the people who can process the material I choose. 'Realization' is an important aspect! Secondly, I try to do things that are obvious; by doing this, you do not spoil material and energy. If you don't spoil material and energy, you have a more efficient product. This in turn gives the opportunity of making profitable products. It sounds very simple but the funny thing is, it often brings new ideas as well.

ARE ANY OF THESE ASPECTS DIFFERENT THAN 10–20 YEARS BACK?

Now I recognize the quality of a material. So, it doesn't start with 'the scrap wood', but it starts with a person who loves a material and wants to do the best things with it. My works become simpler; I am more dedicated to simple things. If you want to do real minimalistic simple ideas, you first of all need to do all the other ideas. Awareness comes afterwards!

IF WE SAY 'MATERIALS & SUSTAINABILITY'... ?

Everybody would like to maintain the way they live. We know that cars pollute, but we still want to live far from our works. This is luxury. We know already for 20 years that we have to cut down and consume less because sources are limited. Sustainability becomes more and more important, and I have become more aware. But it has always been an intuitive part of my work. Since we started our company, we have done everything similar to how we did it before: simple, dedicated. We decided to do everything ourselves: designing, producing, delivering and so forth. I am a maker, I like doing everything myself. This is one of the most important themes in our company. We didn't understand at the outset that it was different to how other people were designing. Now, if people try to give me the stamp of 'environmentally friendly' or so on, I always say that it is a small company who tried to be as rational as possible. That's why we survive. We try to make beautiful products from old, waste materials.

WHAT ABOUT 'MATERIALS & TECHNOLOGY' ...?

I think the western world puts a lot of effort into 'goals'; it puts their goals a long way ahead and

BIOGRAPHY

Piet Hein Eek embodies all the characteristics of a true entrepreneur who has methodically built an enterprise of significance amid the world-renowned Dutch design scape. He studied furniture and industrial design at the Design Academy of Eindhoven. Since 1992, he has developed a portfolio of work that illustrates a consistent willingness to explore and experiment with materials.

Image Credit: © Piet Hein Eek

tries to reach them with novelties, with new things. I put my energy into those machines and materials that have often already been abandoned. Nobody sees the quality of it, but if you don't take as a goal to do something the newest or the best, but instead to do it the most efficiently, often the road which is already there brings you to that goal. I think we put a lot of energy into gaining new knowledge but don't put enough energy into making existing knowledge deeper. So we have a society which very much focuses on the 'new'. A craftsman makes the same cupboard hundreds of times; each time better and better. In the end, you never see ugly antiques. It is very difficult to make a good design at once. If you keep trying with existing materials instead of new materials and new processes, you will improve it. We shouldn't miss the possibilities of things that already exist. New is of course not totally bad; but you should first put enough energy into the old ones.

MATERIALS & USER INTERACTION…?

It is important that a sitting element should be functional, aesthetical, and strong. It should make people happy. Part of the image of our company is the fact that we are honest with energy and material, and it is very transparent; especially in the way it is sold and communicated to the user. Most of the products we see in the market today are without identities. You don't know who the designer is; you don't know how it was made; you don't know its materials. In our case, you know everything! Even if you purchase the product in the USA, you buy this table from Piet Hein Eek, from this Factory, you order its colour and size, and you have your own number in our production facility. Altogether I think it makes an honest product for the user, and a unique experience. So it is not only the product that interacts with the user, but the whole story behind it.

FROM WHERE DO YOU GET INSPIRATION AND INFORMATION FOR YOUR MATERIAL CHOICES?

It is the other way around for me: I am very much inspired by materials, which are almost always the start of any idea I have. I use materials that are not normal to use for particular purposes. In general, my philosophy to any material or any design is to do or use things that are obvious. So if I have a machine, and if I see a material that is possible to be processed with this machine, I will try it. I look everywhere for materials, and use simple materials in a way that is different than the traditional. So it is almost the case that every design of mine is inspired by the material itself.

HOW DO YOU THINK MATERIALS SHOULD BE TAUGHT IN DESIGN EDUCATION?

I gave one master lesson at the Eindhoven Design Academy. I think it is important that students learn to make things. Instead of thinking about all kinds of concepts for seven weeks and trying to realize a project in 1—2 weeks, they should make it from the beginning. I followed this strategy. I told them that we have a material, which is plywood, and we have cardboard available for models. For the second week, I wanted to receive five designs (scale models) in cardboard; for the week after, I wanted to receive the designs in plywood (again as scaled models). We selected democratically the one best design from amongst each set of five. Then, one week later, the students made it from plywood at 1:1 scale. The results were really good: nice products, a very fast moving process, and very importantly the students talked about it!

Then the students were allowed to choose their own material for their design. We got the first models and they were really bad! And I loved that; because I asked what they thought about it; what had gone wrong. They all answered that they didn't have the material as a starting point. Students need boundaries; they need to be dedicated to a material. If you can choose from everything, you don't even choose! So they learned that they have to choose from the beginning. If you choose fast, you can put your effort into making better ideas and thinking about the possibilities.

Waste Scrapwood Table

Client: Piet Hein Eek

Year: N/A

Product Material(s): Scrapwood, high gloss lacquered

Brief Description: "*Often you throw materials away that are usable because it is too much work to process them, to do something with them. I was annoyed with the fact that everything should be done within a hurry. And you don't have time to do the work you want to do. In this product, I acted as if labour cost was nothing and material was a fortune. The result is the ScrapWood Table, which is one of our most successful products. I expressed myself, and my feelings about labour and time, in this product; and people recognised it.*"

Image Credit: © Piet Hein Eek

99,13% Plate Steel Cabinet

Client: Piet Hein Eek

Year: N/A

Product Material(s): Steel

Brief Description: "*The cabinet is produced with less then 1% left over from the blank metal sheets. Even the holes to make connections are counted as a left over. If we didn't count those, it would be 0% left. We have variations of this. The product is respectful to the material and to the energy of production!*"

Image Credit: © Piet Hein Eek

Philips Cabinet

Client: Piet Hein Eek

Year: N/A

Product Material(s): Aluminum

Brief Description: *"The idea behind this product arose after Eek found a number of metal framed doors discarded at Philips' dump. The cupboard came about as a logical result of the size, character and former use of the door windows. This project illustrates a long-standing attraction by Eek to everyday items rather than contribution to the design of high-end design pieces."*

Image Credit: © Piet Hein Eek

Box in a Box in a Box

Client: Piet Hein Eek

Year: N/A

Product Material(s): Wood

Brief Description: "*The product is made from a beam that existed in unintentionally large quantities of in the Factory. Eek thought to find a way to use the beams efficiently, making a design to cut each time a new box. So with the left over internal material, you make another box. There is no waste material; the product makes the maximum with a minimum amount of material.*"

Image Credit: © Piet Hein Eek

SECTION 3

Futures through Materials

Technological developments provide designers with new materials and manufacturing processes to work with. In this section, the contributing authors discuss the design potential of important cutting-edge materials and manufacturing technologies.

CHAPTER 14

The Next Generation of Materials and Design

Rob Thompson[1] and Elaine Ng Yan Ling[2]

[1]*Designer, Material Specialist and Author,* [2]*Founder, The Fabrick Lab*

CONTENTS

Products are the result of the delicate touch of a craftsperson or demonstrate how a designer has mastered highly mechanised production. There is an opportunity for new material experiences to be explored and defined. Designers can lead this process, combining the technical and emotional aspects of material development, to create richer, more meaningful and future relevant product experiences. This chapter will explore some of the most exciting collisions between design, engineering and material science, whereby the practical and creative aspects of material development are in sync.

Technical development is driven by a desire to solve fundamental problems with innovative solutions. Many of the products that surround us are the result of decades, or even centuries, of continuous improvement. Performance-driven solutions are often aesthetically appealing, because they are refined and demonstrate an acute attention to detail. Lightweight racing sails, such as those manufactured by North Sails, are formed by laminating high-strength fibers along the lines of stress between two plastic films. The composite material, which has been paired-down to the absolute minimum, illustrates the lines of strength and stress on the sail, which is both elegant and impressive. These pioneering developments influence running shoes and furniture alike.

There are humble examples too, of products that surround us in our daily lives, such as lighter weight packaging. A collaborative industry working group, involving Quinn Glass, Tesco, Kingsland Wine &

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Spirits, and WRAP, developed a wine bottle that is 30% lighter than the average 500 g. This virtually invisible innovation will save an estimated 150,000 tons of packaging each year in the United Kingdom alone (WRAP, 2012).

In contrast to technical problem solving, creative design exploration is a process of lateral thinking, whereby many different concepts are explored, even if they may not be considered at first to be the ideal solution (Bono, 1970). Designers are typically restricted to a palette of well-understood materials that are readily available, affordable, and accessible. With knowledge of materials, it is possible to challenge the mechanics and manufacturing with intelligent solutions that may otherwise have gone unexplored (Thompson, 2011).

Designers are in a unique position to combine the practical and emotional aspects of material development. This has become increasingly important since the continuous growth of productivity induces a process whereby products become cheaper, more readily available, and consequently less valuable. You are less likely to become emotionally attached to something that is cheap to replace (Hinte, 1997).

The first part of this chapter outlines technical material developments—such as lightweight composites, high-strength fibers, and bioplastics—that are having a positive impact on design, and the second illustrates how designers are redefining product experiences, challenging our expectations about what is man-made.

ADVANCED MATERIALS AND MANUFACTURING

Materials continue to get lighter, stronger, and smarter. There have been many incredible innovations brought about by the search for solutions to technical challenges, such as lightweight composite structures to enable faster, lighter, and more fuel-efficient transportation; amorphous metals that are twice as strong as titanium and can be shaped as easily as plastics; and mass-produced packaging designed to biodegrade and so not contribute to landfill. Performance-driven material development provides designers with a continual source of inspiration (Manzini, 1986; Thompson, 2007). This section will explore some of the most exciting developments that are having an impact on design, or will do so in the future.

Superlight

Creating lighter weight structures requires innovations in both materials and production. Many ideas come from observing the beautiful efficiency of natural structures (Beukers and Hinte, 2001; Stattmann, 2003). Wood is a composite material, made up of cellulose combined with lignin. Trees live in their environment and their trunks, limbs, and joints strengthen as they grow and in response to applied loads. Similarly, man-made fiber-reinforced composites, such as carbon fiber-reinforced plastic and metal matrix composite, can be tailored to meet the requirements of an application. The density, fiber type, fiber orientation, and binder can be combined in a multitude of ways. The combination of high strength and versatile manufacturing has resulted in widespread use of these materials for high performance and demanding applications.

Carbon fiber composites were once limited to Formula One, racing boats, and aerospace. In the last decade, the price has fallen significantly, because production is becoming more efficient, while automotive and aerospace applications are increasing. As a result, the distinctive visual properties have been utilized in consumer products, including smartphones, watches, and even stationary. The most compelling applications, however, utilize the mechanical properties too, such as Alberto Meda's *Light Light Chair*. His first carbon fiber chair, designed in 1987, weighed less than 2 kg. The chair was so efficient in its use of materials that user testing demonstrates it was too lightweight and high-tech in appearance to be accepted by the wider public at that time (Antonelli, 2003). More recently, Terence Woodgate and John Barnard used carbon fiber and Formula One engineering principals to produce the super thin and lightweight *Surface Table* (Figure 14.1).

Composites dominate applications that require maximum strength for weight. They are based on the principle that combining the performance of two or more materials produces superior mechanical performance—such as fiber-reinforced plastics, wood laminates, and sandwich constructions—without the compromises. However, with current recycling technology, it is very difficult—impossible in most cases—to reclaim 100% of materials if two or more are permanently joined together. As a result of this challenge, there has been significant progress in the development of materials that have the benefits of composites without requiring two different materials. So far, this has been achieved in one of two ways. Either a material is foamed, to create a lightweight three-dimensional internal structure encapsulated between the surface layers (the size of the foam cells is carefully controlled for optimum weight-specific strength). Or, the same type of material is produced in two different formats, with complementary mechanical properties, and then joined together permanently. For example, self-reinforced polypropylene (PP), combines drawn PP fibers (anisotropic) into a sheet material (isotropic). This consolidation produces a material with all the properties of PP (such as excellent impact resistance, even at very low temperatures) with the added tensile strength of a drawn PP fiber. Samsonite makes very good use of these properties in the Cosmolite luggage collection, which is their strongest and lightest range.

High-performance fibers developed for racing boat rigging, climbing, and parachutes provide creative opportunity for designers, artists, and architects. Examples include ultrahigh-density polyethylene, an exceptional material that was developed in the 1970s by DSM, who manufacture it under the trade name Dyneema®. As a drawn fiber, it is 15 times stronger than steel for the same weight. Tenara® fiber is manufactured from expanded polytetrafluoroethylene (PTFE), the chemical name for Teflon® from DuPont. Expanded PTFE is two to three times stronger than conventional PTFE, resistant to ultraviolet light, easy to clean, and colorfast.

FIGURE 14.1

Surface Table by Terence Woodgate and John Barnard for Established & Sons. *Image reproduced courtesy of Established & Sons www.establishedandsons.com.*

Sustainable

It is ironic that plastic, a material whose longevity is phenomenal, is used to produce disposable products. As a result, there has been a concerted effort to develop effective biodegradable solutions, led by the major polymer suppliers including BASF, DuPont, and Bayer. Biodegradable petroleum-derived plastics are either compostable (partially biobased) or oxydegradable (contain photoactive or thermoactive ingredients). Oxydegradable plastics fragment into tiny particles, but their biodegradability is not scientifically proven. Biobased plastics are derived from renewable biomass sources, require 20–30% less energy to manufacture than petroleum-derived plastics, and some are compostable (Thompson, 2013). Either starch is used in its raw state or it is further processed by bacterial fermentation to produce biobased monomers, which are polymerized into bioplastics. The source of biomass is critical because the impact of growing the crops may outweigh the benefits—for instance, deforestation, genetic modification, the use of petroleum-powered machinery for production and transportation, or the displacement of local food production and increased food prices.

Injection molded plastic has become the benchmark in commodity products, against which bioplastics and other alternatives have to compete. If they are not as durable, cheap, or moldable, they are quickly dismissed. Polyhydroxyalkanoate (PHA) and polylactic acid (PLA) are two of the most widely used bioplastics. PHA has similar properties to PP or polystyrene (PS), depending on the exact ingredients. PLA, however, has similar properties to PS or polyethylene terephthalate, which is commonly used in drink bottles. This presents a challenge for designers: not only are these materials virtually impossible to be separated from synthetic polymers, for recycling, for example, but also designers cannot use them to differentiate their products from the mass of molded plastic products. Therefore, biobased material developments that are not created as a direct replacement for synthetic plastic can create fresh opportunities for design. An example of this is Treeplast®, which is made of wood (50–70%), crushed corn, and natural resins. The exact ingredients vary according to the requirements of the application. It can be processed by injection molding, but has a very distinctive woody appearance (Figure 14.2). The basic material will biodegrade very rapidly in water and within 4–6 weeks in soil. Another grade is

FIGURE 14.2
Injection molded Treeplast® biobased plastic.

available that is water resistant and longer lasting. The unique properties of the material present opportunities for designers to explore, including touch, smell, and appearance.

Structural biocomposites are an exciting area of innovation. Plant fibers, such as hemp and flax, are being used to reinforce composites for the automotive industry to reduce weight, cost, and environmental impact. They are replacing conventional composites, such as glass fiber-reinforced plastics, for both structural and decorative applications. For example, flax-reinforced plastics have similar energy absorption (by weight) to synthetic materials such as carbon and glass. Research continues and new material formulations are continually being developed. Industrial hemp is an important sustainable material that thrives in most climates with minimal pesticides and herbicides (Roulac, 1997). The bast fibers used in textiles, papermaking, and biocomposites, for example, are long, strong, durable, antimicrobial, and biodegradable. However, cultivation is limited to only a handful of countries due to its close association with marijuana (a psychoactive drug).

SHAPING FUTURE MATERIAL EXPERIENCES

During his 1957 study, *Mythologies*, Barthes was witness to plastic becoming the dominant material. The reasons are simple; it is ubiquitous and yet can be mutated to suit any given task, whether functional or aesthetic. A product, therefore, is no longer rooted in its material origins (Kwint et al., 1999). However beneficial this may be, it has also meant we have an overabundance of emotionally shallow inanimate objects. For example, companies such as Walmart, Tesco, and Mono Prix do not expect their cheap semidisposables to last. This is echoed in the choice of materials, manufacturing techniques, and their design. Most importantly, the objects and materials fail to evolve, change, progress, or adapt, which means that over time their value depreciates, personally and economically. For these reasons, we are becoming progressively less attached to our material surrounding, which leads to feelings of impermanence and transience for the future.

Following prolific new product development in the first half of the 1900s, the pace of innovation has slowed (Cowen, 2011; Florida, 2002). Many of the material developments promised over the past few decades, such as nanotechnology and self-healing composites, have failed to materialize on the scale we had hoped. Designers are in a unique position to be able to reinterpret the opportunities presented by such developments, and apply them in creative ways, to bring about a new generation of product experiences. It is possible to make new grades and fine-tune materials to meet specific technical requirements, if the unique properties of the material are well understood. This part will explore how designers can begin to shape future material experiences, by steering material development, to create technically and emotionally innovative products.

Designing materials

Designing materials involves either creating new versions with existing and well-understood ingredients, combined to create a new set of characteristics, or building from the bottom-up, such as with chemistry and nanotechnology. Materials developed from existing ingredients can still redefine product experience, by encouraging us to interact, play, or consume an object in a more meaningful way. Prototyping is a fundamental part of the development process: helping to realize the potential of the material development; explore the look and feel; understand the mechanical properties; and because importantly, when you manipulate new material, you will find new ideas.

Material science innovation is the result of either extracting from the raw material in a new way, or by mixing a unique combination of base ingredients. New material opportunities continue to emerge. In 2011, Anke Domaske, a German microbiologist and fashion designer, developed an organic milk-based fiber. Qmilch® is soft and drapes like silk, but can be washed like cotton. It uses milk that has gone sour and would otherwise be disposed, and requires less energy and water to manufacture than many conventional fibers, minimizing the environmental impacts. While this material is not yet in full-scale production (Bucci, 2012), it does present a new material experience that may be utilized by fashion and interior designers in the near future.

Nanotechnology has been utilized in material development throughout history (Leydecker, 2008). The red color of stained glass windows is created with gold nanoparticles (particle size determines color) and Samurai swords owe their extreme strength and sharpness to nanoscale carbon structures (Reibold et al., 2006). Today, titanium dioxide nanoparticles are used in sun cream to protect us from solar rays, while as a coating on glass it acts as a catalyst in the self-cleaning process. However, the most exciting developments for design are those inspired by nature. Plants and animals have evolved to cope with their environment; in nature, form truly follows function.

There are many examples of engineering that resemble structures found in nature, such as bone, foam, and honeycomb (Beukers and Hinte, 2001). Computer simulation software, based on finite element method, has revolutionized the way we engineer products. Nowadays, it is possible to create very efficient structures, with a detailed understanding of their mechanical limits. Even lighter weight, paired-down, and more reliable structures could be realized if they were strengthened according to the internal and external loads in application, as opposed to a generic calculation. In the future, self-healing additives could enable such structures while creating a new genre of objects that are sympathetic to the environment and context of use.

Thermosetting plastics are formed by mixing two parts, which means that they can be developed to self-heal if a crack forms. Autonomic Healing Research at the Beckman Institute, USA, developed a structural plastic that has self-healing properties. The breakthrough was made possible by the development of microcapsules of dicyclopentadiene that acts as a healing agent with a wall thickness that would rupture when the material began to crack, but not before. The microcapsules release the healing agent, which is catalyzed by chemicals also encapsulated in the material. The liquid material is drawn into the crack by capillary action and polymerizes to form a strong bond with the parent material. Up to 75% of material toughness is recovered by the self-healing process.

Experienced materials

Aging in the form of deterioration illustrates a passage of time, a narrative that manifests itself as wear, fading, stains, scuffs, scratches, and so on. The desire for evidence of the passage of time is fueled by consumers longing for “authentic” and “real” experience, which is somehow a confirmation of their identity, as well as the perceived security of the past (Stewart, 1993). These marks, however, can also be seen as evidence of manhandling, material failure, or poor craftsmanship. This is a distinction that the

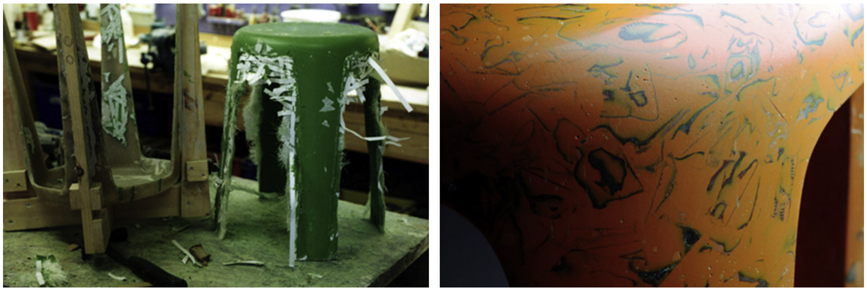

FIGURE 14.3
Material Memories. *Designed by Rob Thompson, 2001*

department store overcomes by using terms such as "collectible" and "hand crafted". Nostalgia and sentiment cannot serve to overcome insecurities that we might have about the future. Instead, they can represent history and a "lived" passage through time, which is affirming.

The choice of materials determines how well an object, and its surface, adjusts to the environment of use. For instance, materials like wood and leather have "lived": they adapt as they grow; wounds healed and weather changed their structure. We surround ourselves with these materials, reassured by their familiarity and pleased by how they mature. Plastics on the other hand are much more challenging.

Material Memories is a design and material development exploration that utilizes the moldable nature of plastic with the aging, idiosyncratic qualities of lived and experienced materials (Figure 14.3). Over time, the colorful material wears and matures, revealing hidden patterns created by the maker, and shaped by the user. The traces of one's own use on the surface of materials make objects feel more "human" and personal, and are thus reassuring. Cleaning, polishing, building, repairing, collecting, and showing off are possession rituals (Koskijoki, 1997). These acts of reshaping or refinishing strengthen the bond between the owner and the object, becoming symbolic and ritualistic.

Deterioration can be functional too (Leatherbarrow and Mostafavi, 1997). It could, for instance, map the use of an object, like a pathway worn into a mountainside that depicts the most sensible and efficient route. In this sense, the form and the speed of the aging process could be used to represent how an object is used most effectively.

The world will continue to develop and change—accelerating all the time—and we may be more able to cope with the inevitable change if we have products that change with us, and feel molded by us, thus confirming a sense of who we are. This is an exciting and challenging prospect, one in which product designers will continue to play a vital role.

Programmable materials

Biological systems are programmed by the seasons, climate, and location. Pinecones, for example, respond to changes in the weather. The scales flex passively in response to rising humidity. They are composed of two layers, which expand and contract, causing the scales to bend. This smart, modular process, known as the pinecone effect, is recreated in textiles, designed to manage temperature and humidity.

FIGURE 14.4
The Clusters Dancing Roof by Elaine Ng Yan Ling, 2010.

Shape memory polymers and alloys allow designers to create materials that respond to specific stimuli, just like in nature. Nickel titanium is an example of a shape memory alloy that has the ability to return to its original, preprogrammed, shape after it has been deformed. The reshaping is initiated by a rise in temperature (or electric charge). Therefore, if the transformation temperature is set below ambient temperature, the material will constantly spring back, a property known as superelasticity. This quality has been utilized in "unbreakable" spectacles, which can be sat on and crumpled. The lightweight frames continually return to their original shape undamaged.

With emerging technologies, designers are beginning to bend the rules, creating new and unexpected behaviors in man-made materials. A dialogue between people, space, and material is created that has never before been explored outside nature. *The Clusters Dancing Roof* combines the properties of wood and textile with shape memory alloy to create a symbiotic material, whose shape and character are determined in part by programming the electroactive alloy and in part by the natural properties of lived and experience materials (Figure 14.4). Over time, the material will behave differently, responding to changes in temperature and humidity, as well as the programmable movements of the shape memory alloy. Data are transformed into an organic movement and become a reflection of the surroundings. This approach to material development could enhance modern architecture and interiors, bringing a subtle and fluid awareness of the outside indoors, evoking harmony and natural movement within an urban environment.

CONCLUSIONS

Rather than an object displaying the qualities of good craftsmanship, mass-produced products and experiences have come to represent culture and mass consumption (Cummings and Lewandowska, 2000; Klein, 2000). It was not until the invention and application of plastic that "designer" products became affordable and widespread. In many cases, plastic gave rise to imitation, because it provided a very cost-effective way to manufacture everyday objects. Until then, imitation materials had always indicated pretension; they belonged to the world of aesthetics, not of actual use (Bartes, 1957).

Creative material development is an exciting aspect of design that is gradually gaining momentum. Creating products with the potential to deliver new material experience helps to strengthen the bond that forms between user and object. Products are by their nature without emotion, unless they are produced with the tender loving care of a craftsperson (Do, 2000; Julier, 1993; Pevsner, 1964), and mass production has created many obstacles for good craftsmanship. The connection between maker, object, and user is being reestablished through the development of forward thinking and engaging products, rich with material quality. This approach to design is enriching our lives, creating catalysts for meaningful, long-lasting experiences.

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CHAPTER 15

Nanomaterials in Design

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CONTENTS

Newly developed materials have long been a source of both inspiration and opportunity for designers. It is hard to imagine, for example, a design world without plastics—themselves once a new material. More recently, developments in carbon fiber and other technologies have made products stronger, lighter, and easier to use. User-oriented devices based on material-related developments in the electronics world—ranging from chips and storage media to interactive touch screens—have literally revolutionized social and business fabrics.

Recently, the attentions of material scientists have turned to developing the world of nanomaterials and nanotechnologies. These descriptive terms are familiar to all but rarely actually understood. Nanomaterials have internal morphological features at the tiny nanoscale—about one-billionth of a meter and equivalent to several atoms aligned in a row (about the width of a single strand of DNA). The thickness of a human hair is around 60,000 nm. The head of a pin is about 1 million nanometers in diameter. As will be discussed more below, metal, ceramic, polymeric, or composite nanomaterials that are manufactured at this nanoscale have remarkable mechanical, electrical, chemical, magnetic, and optical properties that are quite different than those of comparably named macrosized or bulk materials, and, correspondingly, offer unique opportunities to designers and engineers. Nanomaterials are also widely used to make nanotechnology devices, e.g., nanosized electronics or even tiny gear mechanisms. Their usefulness in many technical electronic, industrial, and biomedical domains has already been widely exploited, but the product design world is only slowly seeing transformative applications in other areas. We might soon see, however, product design applications in many lighting and optical areas, self-cleaning and antimicrobial paints and films, and many other areas briefly outlined below.

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NANOMATERIALS IN NATURE AND ART

We may not have understood why or appreciated the nanomaterial contribution, but specific types of nanomaterials have been found in nature and have long contributed to many unique artifacts in our art and design history. In nature, one of the most fundamental of life-sustaining processes—photosynthesis—depends on nanoscale pigments that convert light to chemical energy. Also, the famous gecko that can scamper on walls and ceilings can do so because gecko's feet are covered with millions of nanometer-sized hairs that each produces a very small force of attraction due to molecular interactions. The common mussel depends on nanosized filaments to create a remarkable kind of adhesive that sticks underwater to anchor the mussel to solid surfaces beneath waves. Understanding how nanosized elements play a role in nature is not just a matter of curiosity. The issue of how to connect pieces, for example, plays a major role in the design and shaping of many products. Investigators are well under way in developing new classes of superstrong adhesives that can bind in wet conditions that are based on understandings of nano-related behaviors of geckos and mussels.

In the history of art and architecture, phenomena based on nano-related effects are surprisingly common. Many artifacts have rich colors or beautiful metallic sheens that are attributable to nanoparticles. The famous Lycurgus cup celebrating the 324 AD victory of Constantine over Licinius in Thrace has achieved an almost iconic status in the field of nanomaterial studies. Under normal external lighting conditions, the cup appears green, but then assumes a strong red color when lighted from within—a phenomenon attributable to the unique optical effects possible when nanosized particles (in this case gold) are embedded in the glass (Figure 15.1).

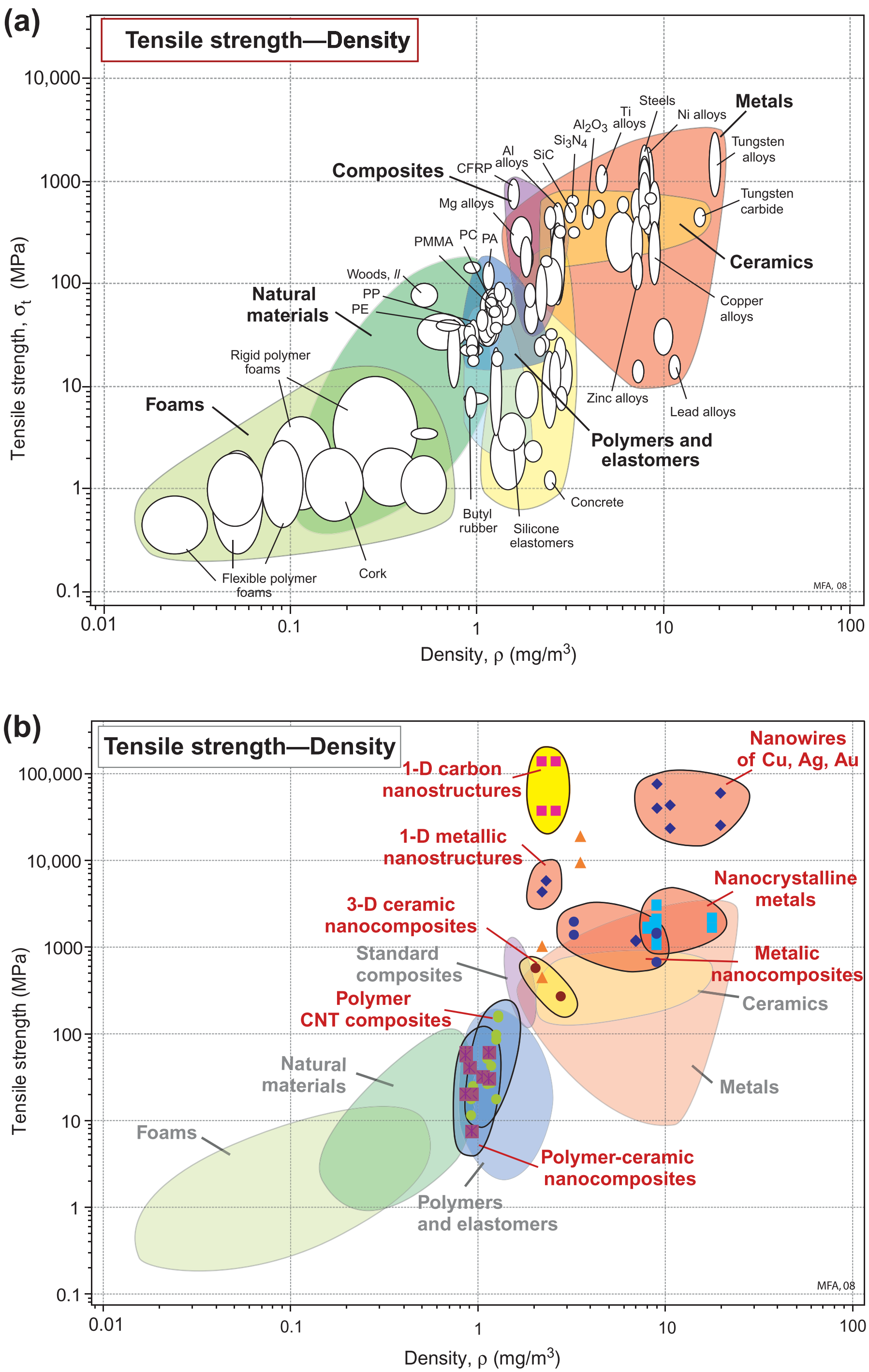
Embedded nanoscale metallic particles, often nanosized gold, are known to have contributed to the ruby-red color of many Medieval era stained glass. The beautiful lusterware produced in Manises, Spain, c. sixteenth century, is prized because of the sheens derived from the firing of metal oxides, which in turn contain nanosized metallic particles. The fabulous intense blues of Mayan wall paintings can be traced to the exact size, shape, and distribution of nanoparticles in the palygorskite clays in the paints used. These phenomena are generally attributable optical effects caused when the diameter of the nanoparticles become very close in size to the wavelength of light. The way light is reflected, scattered, or absorbed is dependent on the size, shape, and distribution of the nanoparticles. Obviously, early users had no science-based idea about why these effects occurred. Despite a seeming endless array of colors now available to designers—often with ridiculous names such as "peach cream"—there is a paucity of products based on colors that can come even close to matching these remarkable historical artifacts and their assured places in our collective memory. With our current abilities to control the size, shape, and distribution of different kinds of nanoparticles, perhaps we can return to thinking more deeply about how color quality can be more effectively utilized in design.

NANOMATERIAL CHARACTERISTICS

What are the characteristics of nanomaterials that have brought them to the forefront of today's material science investigations? As mentioned above, nanomaterials are very small indeed, with dimensions at the nanometer or 10^{-9} m size, just above the size of several atoms placed close together.

FIGURE 15.1

The Lycurgus cup contains gold nanoparticles; it looks green when light shines on it but red when a light shines inside it. *Figure 2.17 in "*Nanomaterials, Nanotechnologies and Design…*" Elsevier. Source: The British Museum.*


(a)
Tensile strength—Density
Tensile strength, σ_t (MPa)
Density, ρ (mg/m^3)
Metals
Steels
Ti alloys
Ni alloys
Al_2O_3
Si_3N_4
SiC
Al alloys
CFRP
Composites
Tungsten alloys
Tungsten carbide
Mg alloys
PMMA
PC
PA
Ceramics
Woods, //
PP
PE
Natural materials
Copper alloys
Rigid polymer foams
Foams
Zinc alloys
Lead alloys
Polymers and elastomers
Concrete
Butyl rubber
Silicone elastomers
Flexible polymer foams
Cork
MFA, 08
(b)
Tensile strength—Density
Tensile strength (MPa)
Density, ρ (mg/m^3)
1-D carbon nanostructures
Nanowires of Cu, Ag, Au
1-D metallic nanostructures
Nanocrystalline metals
3-D ceramic nanocomposites
Standard composites
Metalic nanocomposites
Polymer CNT composites
Ceramics
Natural materials
Metals
Foams
Polymer-ceramic nanocomposites
Polymers and elastomers
MFA, 08

Specific nanomaterial forms include nanoparticles, nanotubes, and other shapes that can be made in small quantities in complex manufacturing processes. Nanocrystalline forms are also possible and in wide use. When nanomaterials get this size, several phenomena begin to occur. The relative surface area to volume ratio of any typical material nanoparticle gets much larger as its diameter decreases. There are orders of magnitude more internal surface area for a given volume of material containing nanoparticles as compared to ordinary bulk materials. This simple fact helps explain many useful nanomaterial applications. Most chemical phenomena, for example, are highly sensitive to the surface areas on which the chemicals act—the more surface area the quicker and stronger is the chemical reactivity involved. A huge number of products and applications depend upon the chemical reactivity of the materials—including self-cleaning glasses and clothing, antimicrobial surfaces, improved batteries, and many others (briefly discussed below)—and thus nanobased versions have improved performances because of their higher surface area to volume ratios. As particles get smaller and smaller, the laws of atomic physics also begin playing a dominate role over the principles governing ordinary materials. In particular, "quantum size" effects come into effect. Here the electronic properties of materials become greatly altered compared to what we now think of as common, e.g., insulators at one scale become conductors at another. Other effects relate to changes in the magnetic properties of materials. These electrical and magnetic effects are being heavily exploited by the electronics industry. Of particular interest to visually oriented designers is the so-called surface plasmon effect (an oscillation of the free electrons at the surface of a metal particle) that causes light waves to be absorbed, scattered, or otherwise affected as a consequence of the size, orientation, and distribution of the nanoparticles, which in turn can be controlled via material selection and manufacturing processes. These effects, unknowingly exploited in some of the historical examples noted above, can potentially be reintroduced into today's design approaches that involve colors and transparencies of materials.

A few basic points must be emphasized here. Nanomaterials are not some particular type of exotic or recently discovered material. Rather, a huge number of materials with familiar names such as zinc, copper, gold, silver, platinum, and others can be produced in nanomaterial form. It is the nanoscale form of the material that gives unique properties. Suitable applications, in turn, depend as much on the primary material form as on its nanoscale properties. Ordinary forms of silver, for example, have long been known to have antimicrobial properties and are already used in many medical devices. Nanoparticle forms of silver inherit these same properties, but can provide similar or greater antimicrobial effects with far less material due to their higher surface to volume ratios and in a more useful variety of forms, and hence be suitable for products that depend on this action—e.g., paints for furniture intended for medical settings where incorporating ordinary silver forms would not be feasible. Nanoscale forms of other materials would inherit those of their parent forms. The tiny sizes of nanoparticles, however, can often exhibit properties quite different from their large-sized parent materials, e.g., different light reflection or absorption characteristics or dramatically improved mechanical strengths or hardness (Figure 15.2).

FIGURE 15.2

Chart illustrating an example of how nanomaterial forms can exhibit improved material properties (in this case for tensile strength) in comparison to large-sized material forms. Note that the scale to the left increases exponentially. *Figure 7.11 bottom in* "Nanomaterials, Nanotechnologies and Design…" *Elsevier. Source: Mike Ashby. Actual chart drawn by D. Schodek.*

It should also be emphasized that many other materials popular with designers may or may not be based on nano-related phenomena. "Smart materials", for example, have mechanical, thermal, electrical, magnetic, chemical, or optical properties that can change in response to an external stimulus (e.g., light or temperature). Common smart materials that have proved very attractive to designers include photochromics that change color in response to varying light levels and thermochromics that change color in response to different temperature levels. A wide variety of other smart materials, e.g., shape memory alloys, have also proved attractive to designers. Many, but certainly not all, smart materials involve the use of nanomaterials and exhibit behaviors based on their unique properties. Many nanomaterials, by contrast, offer useful properties, e.g., enhanced electrical conductivities or much higher mechanical strengths, not commonly considered "smart" in common terminology.

PRODUCT FORMS AND APPLICATIONS

As we look to the present and near future, if we ask the question "what are nanomaterials good for in design?" we find that the answer is rather similar to that of the less than useful broad and undirected question of "what are materials good for in design?" There is no easy answer here since nanomaterials can assume a multitude of forms and have many different kinds of parent materials. A question that proves related is that if nanomaterials are so small, how do we make something big out of them? One way of approaching these questions is to think about what forms nanomaterials can assume (Figure 15.3). Here we find that there are nanocomposites, nanolaminates, nanocoatings, nanofilms, nanosealants, nanopaints, nanotextiles, and others. A common way of creating product-sized objects using nanomaterials is by making them out of nanocomposites. Nanocomposites consist of nanosized particles of one material embedded in a matrix of another material that can easily be produced in bulk form. For example, there can be ceramic-matrix nanocomposites which have silicon, iron, molybdenum, or other types of nanoparticles embedded in a traditional ceramic material to improve high temperature, wear, or some other material property. Polymer-matrix nanocomposites have different kinds of nanoparticles embedded in some kind of polymer matrix to improve toughness, elongation to failure, impact strength, or other properties. Metal matrix nanocomposites are also in use, particularly within the automotive industry. The amounts of nanoparticles needed to achieve these improvements are often comparatively small, say 5–10% by weight of a final composite piece, an important factor given the high costs to produce nanoparticles. Other approaches to making large-sized objects that enjoy the benefits of nanomaterial technologies include using various kinds of nanocoatings or films over bulk materials, or using various kinds of laminates.

The above forms and constituencies of a nanomaterial can then be manipulated to provide specific physical properties that can be utilized or exploited, including basic properties such as mechanical/structural, optical/light, sound, thermal, electromagnetic, and chemical. These properties, in turn, can be used to create many different types of products based on one or more of these physical properties. For example, nanocoatings or various kinds of nanocrystalline surfaces can be devised to yield exceptionally hard (a mechanical property) external surfaces for use on products subject to intense abrasion or used in cutting (e.g., knife blades). Other products, such as different films, rely on enhanced optical properties, while chemical properties are exploited in products such as self-cleaning glasses.

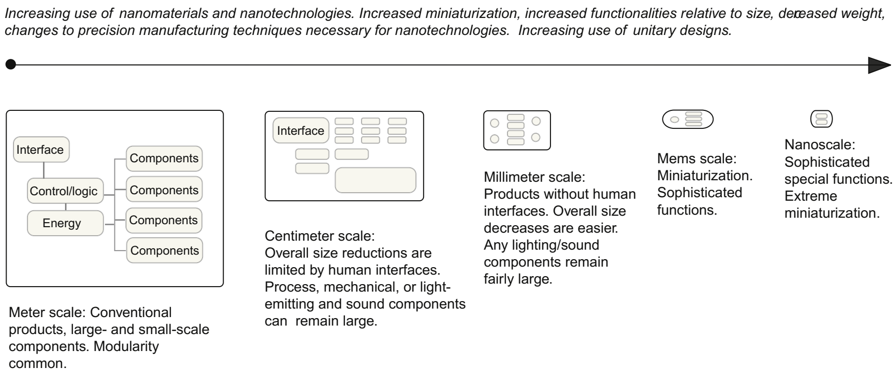


FIGURE 15.3

Impact trends in technologically complex products as a consequence of introducing nanomaterials and nanotechnologies. Some products are expected to become very small, whereas others will have size limitations due to functionalities or interfaces. *Figure 3.18 in "*Nano-materials, Nanotechnologies and Design…*", Elsevier. Originally drawn by D. Schodek.*

Additionally, as will be seen more later, there are specialized functional properties possible, such as antistaining, antimicrobial, antimold antireflection, adhesion, and others.

Many of these nanomaterial forms that have one or more of the basic physical properties noted above are directed toward improving the technical performance of existing products and largely fall within the domain of engineers to push forward. General consequences include the potential for products that have greatly improved existing functionalities while being lighter, stronger, or have some other desirable characteristic. For the product designer, in these domains opportunities are often less about some exotic new functionality and more about general opportunities in making products with improved performance, usefulness, and attractiveness (Figure 15.4). Developments in the electronics domain that rely on the unique electronic and magnetic properties of some nanomaterials, for example, will generally allow engineers to make the internal operative technologies of many devices to be even smaller than ever before. Nano-related improvements in devices with screens will yield sharper, more color sensible, lighter, and tougher screens than ever before. Indeed, we may eventually reach a stage where the product housings are less determined by size requirements to house internal technologies than by designer-led innovations in how users actually interact with products. Interestingly, for many electronic products, battery issues still remain a barrier to this goal. While nano-related technologies offer bright prospects here, and other energy sources may prove to become feasible, the big and hoped for breakthrough has yet to materialize.

Housings for electronic products can potentially become smaller as internal technologies decrease in size, but they can also become lighter, stronger, and stiffer via nano-related improvements in the shell material itself. The addition of nanoparticles with special mechanical properties to the resins used to make carbon fiber pieces, for example, can lead to improved strengths and reduced weights of housings. Interestingly, improving the inherent stiffness of this kind of material is much harder. Other needed properties in housings, such as the ability to conduct or dissipate heat as needed, provide electrical insulation, abrasion resistance, or other characteristics, may also be obtained via choosing

FIGURE 15.4

This cell phone case is made of an amorphous metal. Its hardness, scratch resistance, high polish, and reflectivity add value to the product. *Figure 9.5 in "*Nanomaterials, Nanotechnologies and Design*…" Elsevier. Source: Liquidmetal Technologies; information@liquidmetal.com. Note: This company may no longer be in existence.*

appropriate base materials reinforced with nanoparticles to form a nanocomposite, and/or using nanolaminates or nanocoatings with the right kind of thermal, electromagnetic, or mechanical properties.

Other common products can potentially have improved performances via the use of nanomaterials. Many thin-film product forms hold great promise for different kinds of existing optical or light-related products, including light control films for contrast enhancement, reflective or nonreflective surfaces, color enhancement, and other phenomena. In another area, using nanoparticles in relation to carbon fibers can reduce weights and improve the strengths of the frames of high-end bicycles. Indeed, several brands already promote special claims based on the incorporation of nanomaterials in their products. There is, however, little in the way of nonproprietary data that actually suggests what level of strength or stiffness improvements have actually been made. Better technical performances can also be obtained in a whole range of other common products, including paints and sealants, by the addition of nanoparticles. As noted previously, nanobased adhesives are also being developed that hold great promise. Again, however, there is a paucity of data that actually documents how performance levels are actually affected. Often, proprietary companies (for obvious reasons) make product enhancement claims based on nanomaterial inclusions that do not appear to be founded on solid research or product evaluations, albeit this observation should not detract from the positive potential of the correct use of nanomaterials in products but rather encourage more product testing that will increase our ability to make effective use of nanomaterials in products.

A CLOSER LOOK AT UNIQUE APPLICATIONS

While the potential for improvements in the technical performance and other domains noted above in already available products is proving to be one of the real driving forces behind research into nanomaterials, the potential for unusual or novel applications remains intriguing to product designers and companies seeking to break into the market with new products. In the smart-materials domain, for example, the development of materials that change color in response to changing temperature or light levels (thermochromics or photochromics) led to remarkable outpouring of different applications ranging from the purely novel to the seriously studied application. Here, there were novel bedsheets or furniture based on thermochromic materials, for example, that retained the imprint of a human body for a time after use (thus leading to all sorts of discourse—often somewhat strained—in the design world about "memory of touch" and the like). Many of these applications are still around but few have had a lasting presence. Others, however, such as photochromics for sunglasses, which were once a novelty application, are now commonplace and considered mainstream.

It is surprisingly hard to find really unusual or unique nonelectronic and/or large-sized applications in the nanomaterial world that are not based on some enhancement of an existing product. Some applications, however, do attract attention because of their attractive possibilities. Self-cleaning products are a prime example here and will be used as a case in point. What designer would not like to provide users with clothing or product surfaces that would never need cleaning and what user would not like such performance? There are indeed advances based on particular types of nanomaterials that are being made to reach the goal of self-cleaning products. Here we should first distinguish between the notion of self-cleaning in reference to removal of common dirt and then in relation to odor (i.e., smell removal). The two have entirely different physical bases, with the former having to do with embedded particles and the latter (odor control) having to do with microbial or bacterial effects. Actual visual appearances, however, can be affected by both. Common paints, for example, can become discolored because of both dirt accumulation and from the effects of mold (a microbial fungus).

Self-cleaning effects are found in nature via hydrophobic (water repelling) or hydrophilic (water attracting) actions. Oleophilic (oil repelling) actions are also possible. The lotus flower remains clean because of the hydrophobic action of the nanosized cell surfaces wherein water droplets bead into spheres rather than spread, and then rolling drops pick up dirt particles. Another major self-cleaning approach is through photocatalysis, a natural process that happens when certain materials are exposed to ultraviolet (UV) light (photocatalytic effects are found in nature as well). Self-cleaning actions can be based on any or a combination of the above actions. A nanosurface with roughness characteristics similar to that of the lotus flower can develop hydrophobic actions that lead to cleanliness. A contrasting approach is to make nanosurfaces super smooth and utilize hydrophilic actions. With highly smooth surfaces there is a decrease in the surface energy present and a lower force of surface attraction. These kinds of surfaces are not intrinsically self-cleaning, but are used widely for surfaces where easy cleaning is important. Some antifogging applications are often based on these same actions. In the above, the cleaning actions come from either natural rain impacts or direct wiping—dirt particles loosen and may be washed away but they do not inherently decompose. Photocatalysis processes, by contrast, can actually cause the decomposition of many organic substances that form or are deposited on surfaces. Titanium dioxide or zinc oxides are often used as photocatalytic materials. They are cheap and respond well to UV light. Briefly, exposure to UV light produces electron hole pairs in the material that in turn react with foreign substances to produce chemical reactions that decompose or loosen the substances.

The three actions noted above—hydrophobicity, hydrophilicity, and photocatalysis—form the basis for most current easy cleaning, self-cleaning, and antimicrobial surfaces. The surfaces can be glasses, tiles, enameled panels, and other hosts. Actions can be overlapping. The most popular form of self-cleaning glass currently available has a nanoscale coating of a photocatalytic and hydrophilic material in which dirt particles are oxidized via photocatalysis when exposed to UV rays in sunlight. When subjected to rain or washing, loosened particles easily run off because of hydrophilic action on the surface. Keep in mind that while useful and important, these actions will not be sufficient to remove large clumps—there could still be bird-droppings or insect smears on your windshield (albeit they will be slightly easier to clean off). The processes described above also form the basis for paints, textiles, and other products that are ostensibly self-cleaning. Self-cleaning paints are widely used in the automotive industry.

Antimicrobial materials (variously described as antifungal, antibacterial, and antimold) deal more directly with the issue of bacterial effects. Here, we should note the obvious that some bacteria are useful (e.g., aids in fermentation) while others are less so (e.g., causing smells, deterioration, and discolorations). Some effects, e.g., fungal growths that produce molds, are particularly harmful (including to human health). The two main approaches here to control bacterial effects are through the photocatalysis process noted above, or through the intrinsic properties of certain nanomaterials. Silver

FIGURE 15.5

Surfaces with special hygienic capabilities for use in health care and other environments need to be well suited for easy cleaning, resistant to disinfectants, and have antibacterial action. Surfaces need to be smooth and not have places for dirt to lodge. Coatings with water-repellant action can be used. The finish lacquer used on these wood products consists of a closed-pored antibacterial nanocoating that seals the wooden surface. Several layers are used. *Figure 10.19 in* "Nanomaterials, Nanotechnologies and Design…" *Elsevier. Source: Kusch—a German Company.*

or copper surfaces have long been known to control bacteria spread in hospitals or other medical settings. Paints or coatings with nanosized silver or copper particles are now widely used for the same reason but for reduced costs and higher efficiencies. Typically, these products are not panaceas but they do aid in reducing bacterial spread (Figure 15.5).

As was mentioned, several approaches are often used concurrently. The fashion industry has explored various nanomaterial applications to improve fabric properties (e.g., increased strengths), improve cleaning ease (e.g., hydrophobic fibers), and reduced odors (e.g., inclusion of silver or palladium nanoparticles). Typically, benefits are as yet marginal and there are few reliable studies as to the efficacy of these approaches in commercially available textiles. It appears that we will still have to wash our socks for some time.

CONCLUSIONS—AN ARRAY OF OPPORTUNITIES

In closing, it should be noted that a host of other applications as yet not mentioned exist. Certainly, there are many more developments in the electronics area. We might soon see, for example, product design applications such as complexly curved touch screens that are hard, transparent, and highly efficient that are made possible through the use of graphene—a sheet form type of carbon only several atoms thick. Many other developments will undoubtedly occur in the light and optical arena. The medical/pharmaceutical industry is exploring everything from targeted drug delivery to bone growth enhancement applications. Indeed, potential electronic and medical/pharmaceutical applications provide the primary economic drivers behind the development of nanomaterials and nanotechnologies. The automotive and aerospace industries are huge users of applications ranging from a myriad of electronic devices to paints and many other applications. The cosmetics industry is a controversial user of nanomaterials for various makeups and skin care products (many based on nanoforms of titanium dioxide) that have the potential for not only positive care enhancements (e.g., improved safety against harmful UV rays) but also which many think have serious human health concerns when applied to the body. The sports industry is an early user and proponent of new material applications—as it has always been—as both individuals and companies seek improved performances of everything from tennis rackets to golf clubs and bicycles. The plastics industry is rushing to explore drink bottles that better keep pressurized gases from migrating through bottle walls. Applications are also emerging in unexpected areas, such as processes for desalinating salt water to make usable fresh water.

In all these industries, it is interesting to note that it is often avid material scientists that sometimes make the most far-reaching claims for how their developments might change the world, but who do so often without a complete picture of the broader context in which their developments might be used. A public health scientist once noted, for example, that we had best be very careful in seeking to destroy bacteria via antibacterial applications by noting that many bacteria are helpful and fundamentally necessary to human health and environmental ecology. All bacteria are not simply harmful as is sometimes implied. There is a role for product designers here to explore all aspects of how nanomaterials and nanotechnologies are used within our society and to help weigh claims that are often competing or see to it that claims are rigorously evaluated.

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CHAPTER 16

Sensing and Energy Harvesting Novel Polymer Composites

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CONTENTS

INTRODUCTION

Often, the technical specifications for the properties of materials to be used in products exceed those that can be met by a single class of materials, such as polymers, metals, or ceramics. Sometimes, such limitations can be overcome by combining two classes of materials in a single material product, i.e., by making a composite. In such composites, one of the two material classes is responsible for providing one set of desirable properties, while the other material is responsible for providing another set of desirable (rather different) properties. The shape and volume fraction of the noncontinuous phase in the matrix material is then the free parameter to tune the properties of the composite material.

The use of composites to reach special combinations of mechanical properties is well established and has led to the development of easy processable thermoplastic polymers with granular reinforcing materials for consumer products, thermoset polymers with continuous fibrous (glass or carbon) fibers for high strength—low weight sport products, rubbers with continuous (steel or aramid) fibers for

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flexible yet dimension stable tires, metal sheets interspaced with (glass) fiber prepregs for fatigue-resistant aluminum-like aircraft fuselages, and many other commercially available composites.

However, there is an increasing need for materials which combine desired functional properties such as load sensing, energy harvesting, temperature sensing, actuating, etc., with a minimal performance in mechanical properties. So far, such smart materials have been optimized to maximize their new functionality often at the cost of other properties and/or their potential to be fully integrated with other materials from which the product is made. Typical examples are the problems related to integration of silicon-based solar panels into flexible products, touch-based sensors in plastic domestic appliances, energy harvesting from naturally occurring vibrations, pressure sensors in tires, etc.

In this chapter, we describe a new set of functional composites based on (piezo) electric ceramics, either in granular or fibrillar form, and thermoset or thermoplastic matrix polymers. The polymer matrix provides routes toward easy integration with the external or internal structure of the main body of the product. The active lead zirconate titanate (PZT) material allows a coupling between mechanical forces and displacement and electrical power or signals. Earlier attempts to build such composites yielded low-quality products, since the desirable functionality of the PZT is easily lost. However, in this chapter we describe the potential of aligned or structured granular composites, which have very attractive functional properties, yet maintain easy processing and easy integration with surrounding polymeric structures. The potential of the new composites is illustrated for touch-based switches and strain energy-harvesting devices.

BRIEF INTRODUCTION TO PIEZOELECTRIC MATERIALS

Piezoelectric materials have the unique property of being able to convert mechanical energy into electrical energy and vice versa. The working of piezoelectric materials is shown in Figure 16.1.

Note that the conversion or creation of electrical energy requires electrodes to be placed on opposite sides of the sample. In the example shown in Figure 16.1, the applied force or displacement is

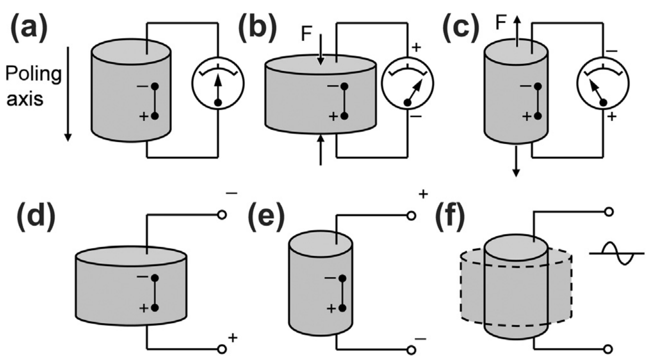

FIGURE 16.1
Schematic diagram of the working principle of a piezo material for sensing (converting an applied force or displacement to electrical energy) (a)—(c) or actuation (converting a potential difference into a shape change) (d)—(f).

perpendicular to the electrodes. Although this is not necessarily the case, in this work it will be the only case considered.

The actual piezoelectric effect is due to a minute shift in the relative position of atoms in their crystal structure upon the application of a displacement and the deeper physical mechanism is described in detail in dedicated textbooks. The piezoelectric process has been found both in natural minerals (such as quartz), synthetic ceramics (such as PZT: Lead (Pb) Zirconate Titanate), and polymers (PVDF: Polyvinylidene Difluoride). The strongest effects are found in piezo ceramics and these have found the widest application, such as in valves for diesel engines, parking sensors, and contact-driven switches. The strains generated are generally very small (in the 10^{-3}—10^{-5} range) and the voltages, or more precisely the voltage gradients (applied voltage per millimeter electrode distance), are relatively high (1 kV/mm).

Conceptually, the piezoelectric effect will enable designers to design complete structures that generate a signal when deformed: self-sensing structures. The converse piezoelectric effect can even be used to deform a structure by applying a voltage, a truly morphing structure. In practice, the small strains and high voltage gradients have limited the use of piezoelectric materials to specific applications with a high added value such as pick-up phonogram elements (converting topological roughness of classical vinyl records into electrical signals amplified to generate noise or music), sonars and scanners for medical testing (converting a high-frequency signal into an acoustical wave and vice versa), and diesel injectors (converting an electrical signal into controlled opening of a flow channel under extreme conditions of pressure and temperature). In these applications, the actual working element is made of a piezo ceramic using high-temperature ceramic processing routes. The nature of the material itself and the high-temperature processing route implies that the piezo material is used as the core of a discrete component in a device and cannot be integrated into the larger body of a product. So there is a need for materials that have adequate piezo electric properties yet that can also embody daily used products. The most important classes of (monolithic) piezoelectric materials, ceramics, or polymers are intrinsically too brittle or have a very low thermal stability and both materials do not meet the desired combination of properties and potential for full integration with a plastic product.

PIEZOELECTRIC COMPOSITES

The needs defined above have prompted researchers to develop piezoelectric composites in which a piezoelectric ceramic phase (in granular or rodlike form) is combined with a continuous polymer matrix (Furukawa et al., 1979; Newnham et al., 1978). In early studies of piezoelectric composites, a classification was made between different types of composites, which was later widely adopted and has become standard notation for piezo-, pyro- and ferroelectric composites (Newnham et al., 1978) (Figure 16.2).

Of these composites, the 0-3 (there is essentially no connectivity between the piezoelectric ceramic particles, yet the matrix is continuous in three directions) and 1-3 types (there is threadlike connectivity between the particles in one direction only, yet the matrix is fully continuous) have received the most attention.

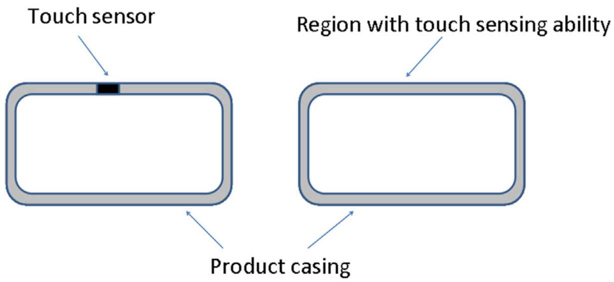

FIGURE 16.2
Schematic difference between a product with a discrete touch sensor and a region with touch sensing ability.

The simplest of these composites, the 0-3 type, generally consists of granular, randomly distributed piezoelectric particles in a matrix (Furukawa et al., 1979). These materials are relatively easy to manufacture but the large differences in particle and matrix dielectric properties are certainly not beneficial to the composite piezoelectric properties unless the composite contains a high volume fraction of ceramic (Dias and Das-Gupta, 1996). The 0-3 composites are easy to fabricate using conventional polymer processing routes and are relatively cheap as the cost of granular PZT is relatively low.

Alternatively, in 1-3 composites, the ceramic phase is fully connected from electrode to electrode. As a result, these composites are largely used in the same applications as direct replacements of bulk ceramic elements. Here, the lower permittivity of the polymer phase is used to increase the sensitivity and the compliance of the polymer phase is used to reduce lateral coupling, for instance, in ultrasound transducers (Manbachi and Cobbold, 2011). The 1-3 composites are generally based on PZT fibers and are very hard to process if the fibers are to be aligned and intact. The high processing costs as well as the higher cost of PZT fibers makes 1-3 composites substantially more expensive than 0-3 composites.

Figure 16.3 shows schematically the discrepancy between the properties of polymeric and ceramics piezo materials and the way the PZT-polymer composites fill the gaps (van den Ende, 2012).

Composites with adequate piezoelectric charge and voltage constants as well as good mechanical ductility are still lacking. Yet such materials would open many new application areas. So there is a need for new composites that combine the good piezoelectric characteristics (in particular their ability to transform displacements into electrical signals or electrical energy) of expensive, rather brittle, and difficult to process 1-3 fiber composites with the easy processing and good ductility of 0-3 particulate composites and the ability to be fully integrated.

Properties of 0-3 composites

As discussed in the introduction, piezo materials can transform an electrical voltage into a displacement (making the material an actuator) or can transform a displacement into an electrical voltage (making the material a load or displacement sensor). The mathematical connection between both parameters is rather complex and can only be described in tensorial form as it is related to the crystal structure of the piezo material. However, for the case of a composite, the strain response as a function of the applied

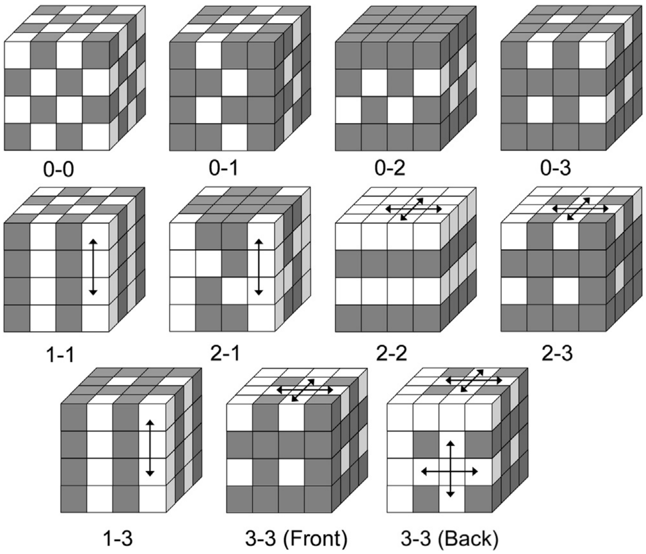

FIGURE 16.3

Classification scheme for piezoelectric composites. *After Newnham et al., 1978.*

voltage can simply be expressed as a scalar, the so-called piezoelectric charge constant, d_{33} (pC/N). Similarly, the voltage response as a function of the applied strain can be expressed as a scalar, the piezoelectric voltage constant, g_{33} (mVm/N). (The subscript $_{33}$ implies that the displacement is perpendicular to the electrodes). The two constants are related to each other in the following manner:

$$d_{33} = g_{33}/\varepsilon \quad \text{or} \quad g_{33} = \varepsilon \cdot d_{33}$$

where ε is the dielectric constant or permittivity.

In a PZT-polymer composite, the sensing and actuating functionality comes from the PZT (or one of the other piezoelectric ceramic) particles only and the matrix is there to mechanically connect the particles and to transmit the electrical field and electrical charges. Hence, it is logical to assume that d_{33} and g_{33} (as well as ε) of the composite depend on the volume fraction piezoelectric material and the intrinsic properties of both materials. Typical dependences of d_{33} and g_{33} on the volume fraction PZT are shown in Figure 16.4(a) and (b), respectively, showing both experimental data and the theoretically predicted dependence by the model presented by Yamada et al. (Yamada et al., 1982).

Figure 16.4(a) shows that the d_{33} value, reflecting the actuating capability, of the composite increases only slowly with increasing PZT fraction and remains very low in comparison to the value of the PZT material itself (less than 10% even for a PZT volume fraction of >50%). The low values are due to the flexible polymer matrix reducing the electrical field over individual particle as well as effectively absorbing the expansion of the PZT particles upon the application of the electrical field. The figure clearly demonstrates that piezo-polymer composites intrinsically have little potential as actuating material.

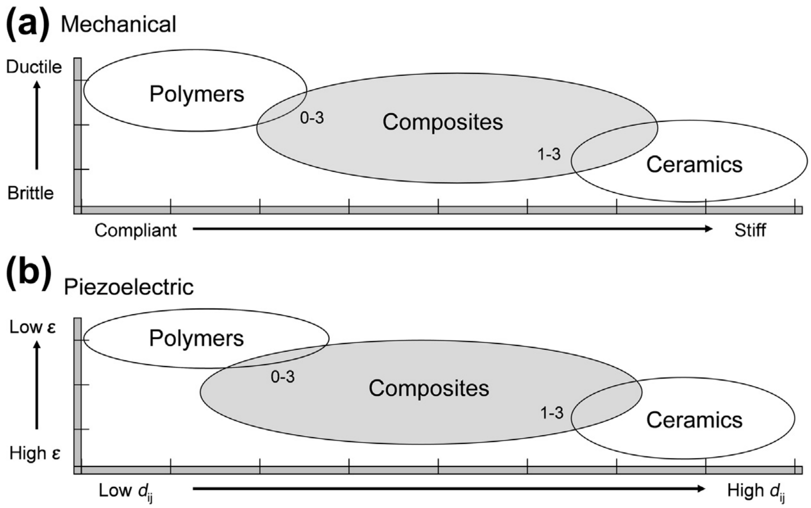

FIGURE 16.4
Schematic overview of the intrinsic differences between polymers and ceramics and the way the composites bridge the gap. *After van den Ende, 2012.*

Figure 16.4(b) shows a much more rapid increase in g_{33} with PZT fraction at low volume fractions, which offers some hope for touch-based switches, impact load sensors, and other sensors involving applied loads or pressures, yet the absolute value of g_{33} remains low. The low absolute value is due again to the imperfect transmission of the displacement and charge coupling between the matrix and the PZT particles. However, in this case, the low stiffness of the polymer matrix (a low modulus material) means that the applied load is carried extensively by the (higher modulus) PZT particles, resulting in an adequate response. So, piezo-polymer composites hold some promise as a "sensing" material generating electrical charges as a result of the application of a load or a deformation. However, it is essential to increase the coupling efficiency and to get materials with a higher g_{33} value at low PZT fractions. The most obvious parameters to adjust are the dielectric constant of the polymer as well as the spatial distribution of the particles in the matrix.

Aligning piezo particles in the polymer matrix

An obvious way to increase the "sensing" capability of the composites at a fixed volume fraction of piezo material would be to somehow align the particles in the direction of the load to be applied, as then the load transfer and charge transfer between particles becomes much better. Such a stringlike arrangement of particles in the direction perpendicular to the sample surface cannot be obtained by regular polymer processing routes. However, Randall et al. (Randall et al., 1992) realized that dielectrophoresis (DEP), the rotation and spontaneous alignment of discrete particles dispersed in a low viscosity matrix under the influence of a fluctuating electrical field, can be used to align particles in polymer matrix. (The DEP process as such may not be familiar to designers but can be regarded as equivalent to the high school experiment of aligning magnetic particles in between two magnetic poles.

In such an experiment, the magnetic particles line up nicely in threadlike structures. In the DEP process, the particles line up in similar threadlike structures under the influence of an electrical field.) The process of spontaneous alignment of individual particles along the electrical field lines followed by lateral shifts of the particles to form threads can be appreciated from Figure 16.5, which shows the progression of the alignment of short PZT fibers in uncured epoxy during DEP. At $t = 0$ s, there is no alignment and the particles are randomly and uniformly distributed. At $t = 105$ s, the particles are relatively well aligned into threadlike structures. This condition is then frozen in as the curing process of the polymer proceeds.

After fully curing the polymer and consolidating the structure of the composite, the PZT material must still be poled to get effective sensing behavior. It should be pointed out that the electrical fields applied in aligning the particles are relatively high, typically 1 kV/mm, so the method is primarily suitable for thin-walled products or films of up to 1 mm thickness only. However, once created, such structured films can be easily integrated in thick-walled polymer products, and be stacked and consolidated, to give more robust products. Furthermore, for many consumer products, a wall thickness of about 1 mm is not uncommon.

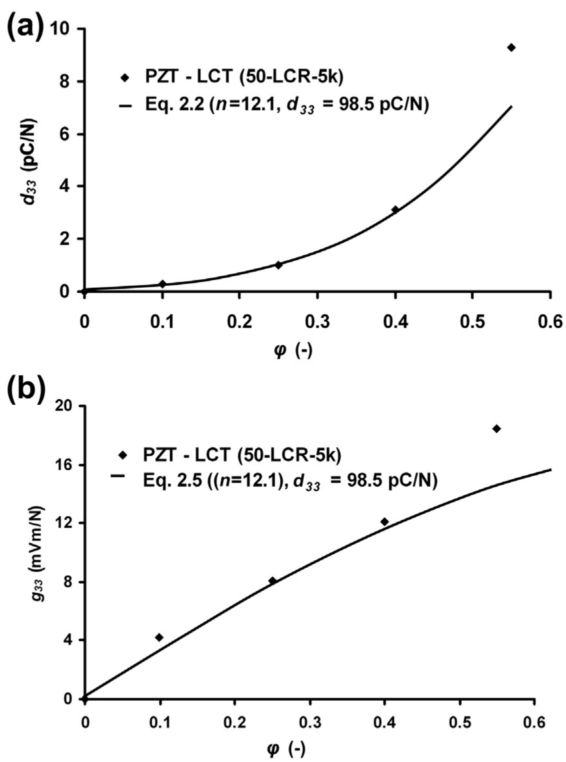

FIGURE 16.5
PZT volume dependence of the d_{33} (a) and g_{33} (b) values for a PZT-polymer composite. *Data from van den Ende et al., 2007.* For the complete description of the fitted dependencies, see the original text.

FUNCTIONAL PROPERTIES OF ALIGNED PZT-POLYMER COMPOSITES

It will be clear that the final properties of such aligned composites depend not only on the volume concentration of the PZT particles but also on the degree of perfection of the alignment as illustrated schematically in Figure 16.6 for short-fiber (Figure 16.7(b)) polymer-PZT composites.

Van den Ende et al. (van den Ende et al., 2010a, 2012a) have developed elegant models to quantify the degree of alignment for structured particulate and structured short-fiber composites and to predict the final properties of such composites. Figure 16.7 shows the measured and calculated behavior of d_{33} and g_{33} for such composites as a function of the volume fraction PZT (short) fiber for different effective fiber lengths.

Figure 16.7(a) shows that the d_{33} value increases more rapidly with volume fraction than for unstructured composites and that the increase is more rapid for longer fibers than for shorter fibers, as is to be expected intuitively. The d_{33} value saturates to a value of about 100 pC/N at a volume fraction of about 25%, which is a much more attractive combination than for 0-3 composites (it should be pointed out that the PZT fibers used had a higher intrinsic d_{33} value than the granular materials used for the 0-3 composites).

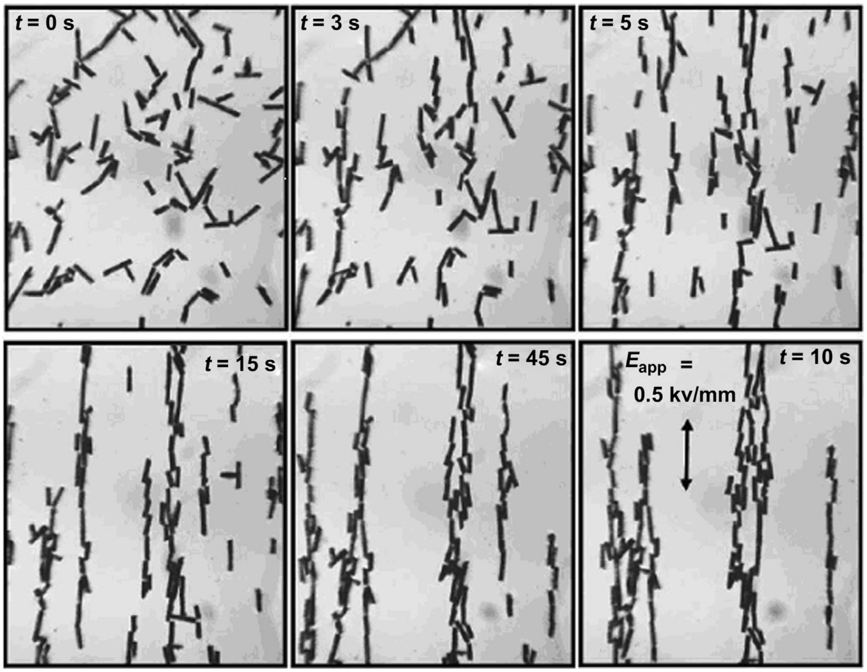

FIGURE 16.6
Visualization of the alignment and thread formation of short PZT fiber-polymer composites during dielectrophoretic processing. *Data from van den Ende et al., 2012a.*

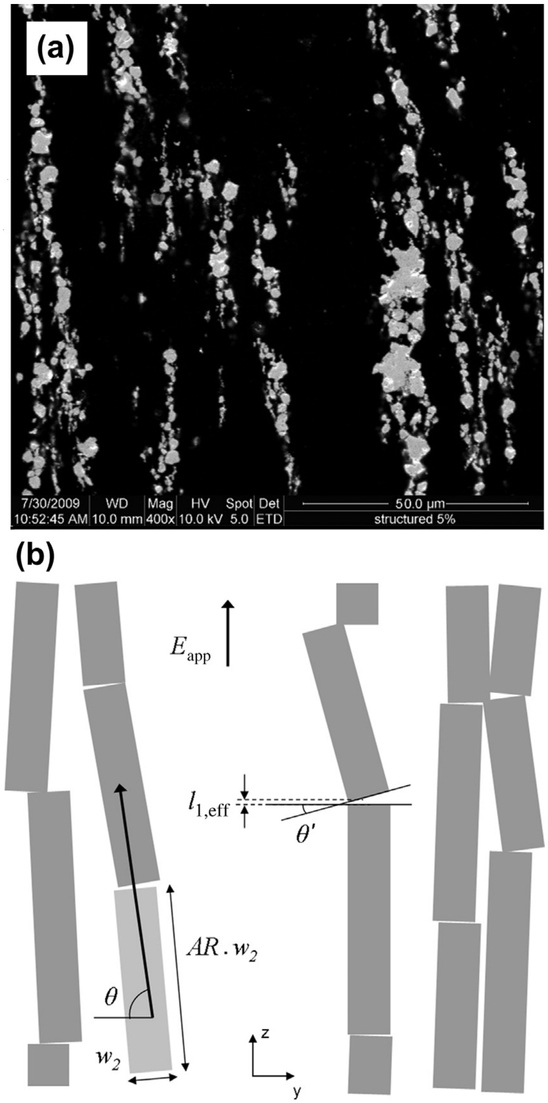

FIGURE 16.7

Experimental variation in particulate alignment after dielectric processing (a) and schematic representation of local variation in alignment for short-fiber composites (b). *Figures from van den Ende et al., 2010a, 2012a.*

However, the most interesting results are shown in Figure 16.7(b), which shows the g_{33} value as a function of the volume fraction PZT for various fiber lengths. Now, the g_{33} value shows a very clear and relatively high maximum of 400 mVm/N at only 3% volume percent PZT. This is a very attractive combination of good sensitivity at a low volume fraction PZT. The low volume fraction makes the material essentially to have similar mechanical properties as the polymer matrix and this offers a large number of opportunities to fully blend such composite materials into larger polymer structures such as covers of electrical or domestic appliances.

Using functional composites for switches and contact sensors

Piezoelectric materials are widely used as touch-sensitive sensors and switches. PZT ceramic disks are of particular interest as they have a high sensitivity, a high g_{33} value. However, they have some important drawbacks: first of all, they are ceramic and hence hard to process as well as inherently brittle, so fracture prone. Furthermore, the signal they produce for a specific load depends on the temperature, which creates significant problems in the further electrical circuitry. Finally, a major problem remains the integration of such disks into domestic or industrial appliances made of plastic. Such problems do play a much smaller role in the PZT-polymer composites just discussed and it is feasible to integrate such functional composites in the larger product by simple thermal processing (thermal welding) or by coforming processes (such as coinjection).

The use of such composites as touch-based sensors has been demonstrated in van den Ende et al., 2010b for a disk-shaped bimorph switch. A bimorph is a commonly applied configuration in which the piezoelectric material is loaded in bending and high stresses are generated at low applied loads. A schematic diagram of a bimorph and its use as a switch is shown in Figure 16.8. The series bimorph configuration (actually two layers of oppositely poled piezo material glued together with a common internal electrode to make sure that both the tension and the compression side of the switch contribute to the output signal and do not cancel out) yields a higher output voltage and is less temperature sensitive than a simple monomorph structure of a single disk of a piezoelectric material placed on a backing plate.

As shown in van den Ende et al., 2010b, switches made of (unstructured) PZT-polymer composites do not give a very strong (yet acceptable) signal but are far more temperature insensitive and hold the potential of good fatigue resistance. By structuring the composite material and/or laminating several structured composite films, a much higher output signal can be obtained.

Using functional composites for energy harvesting

Currently, there is a major industrial effort in the development of wireless autonomous sensors to be applied for product health monitoring or distributed sensing. To be truly autonomous, the ability for the device not only to sense and transmit but also to generate and store energy in situ is crucial. There are many methods to power such sensors such as photovoltaic, thermoelectric, and vibration-based power sources. In general, the most optimal energy-harvesting method depends on the prevailing conditions to which the product is exposed.

In certain applications, the product is continuously or semicontinuously exposed to elastic deformations. These can be small-scale deformations under high-frequency resonance conditions or larger scale deformations at much lower frequencies. Energy harvesting from structures undergoing larger scale elastic deformations at low frequencies is called direct strain energy harvesting. Direct strain energy-harvesting devices are essentially thin and flexible foil-type devices that are directly attached to the host structure and follow its deformation and extract electrical energy out of this. One of the applications that is amenable to direct strain harvesting is the smart tire, fitted with sensors, signal conditioning electronics, and data transmission (Matsuzaki and Todoroki, 2008). Powering such devices

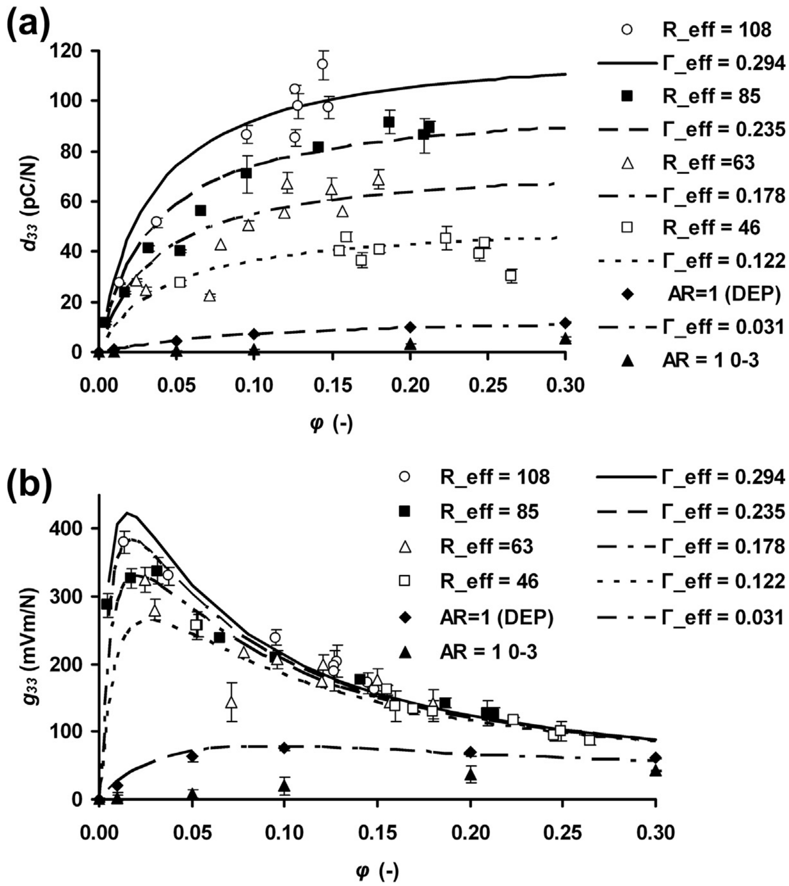

FIGURE 16.8

Dependence of d_{33} (a) and g_{33} (b) on the PZT volume fraction for various effective fiber lengths. *Data from van den Ende et al., 2012a.* For the complete description of the fitted dependencies, see the original text.

via batteries is certainly not optimal and needs periodic human intervention. Devices based on piezoelectric materials seem ideal to harvest energy from the naturally occurring deflection of the tires when in use. However, the current piezo material families, the piezo ceramics and the piezo polymers, are both not suitable for this application. Piezo ceramics are too brittle to survive the harsh shock loading conditions in a tire and fracture and piezo polymers do not have the required temperature stability to survive the high thermal loading ($T > 80°C$) of a tire when cruising on a motorway.

However, the structured PZT-polymer composites described here may offer attractive opportunities as the matrix can be tuned to the prevailing thermomechanical conditions by selection of the right type of polymer and the structuring leads to a decent energy production for a given strain.

Ignoring finer details, the figure of merit (FOM_{EH}) for the energy-harvesting capability of a piezoelectric material (able to survive the prevailing thermomechanical conditions for a sufficient number of cycles) is given by (Rodig and Schonecker, 2010).

$$FOM_{EH} \approx d_{33} \cdot g_{33}$$

Now, this is very interesting as the work on the properties of structure short fiber PZT-polymer has shown that the highest g_{33} values are obtained at low volume fractions of PZT (3–8%).

The use of structured PZT-polymer composites for direct strain harvesting in a tire has been demonstrated by van den Ende et al. in (van den Ende et al., 2012b). Figure 16.9(a) shows the setup and Figure 16.9(b) shows the experimental and calculated charge output for different patch lengths (Figure 16.10).

Figure 16.9(b) nicely shows the cycle of tension–compression–tension as the tire rolls over the counter "road" surface ($x = 0$ means that the center of the patch coincides with the center of the tire–road contact zone). The charges generated per cycle and per patch are relatively small and still lower than that of commercially available patches using embedded continuous PZT fibers (truly 1-3 composites), yet the newly developed composites show a much improved stability under cyclic testing and will outperform the existing material at large numbers of loading cycles. (A tire will do typically 60–200 $\times$ 10^6 cycles during its life.)

Finally, it has been calculated that even for nonoptimized composites, coverage of the entire inner surface of the tire with patches of the appropriate length (of the order of the typical contact length) will

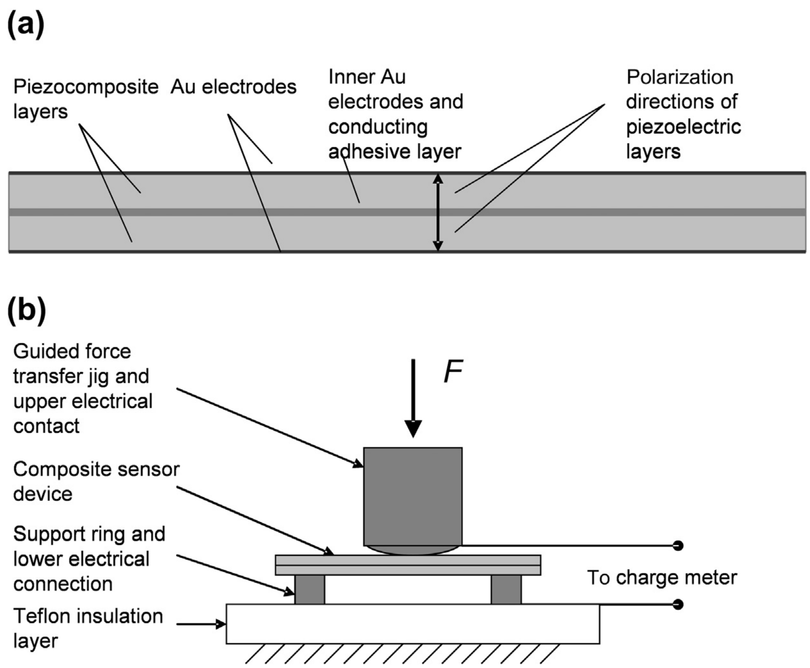

FIGURE 16.9
Schematic overview of the arrangement of a series bimorph (a) and the testing configuration for pressure loaded switches (b). *Originally published in van den Ende et al., 2010b.*

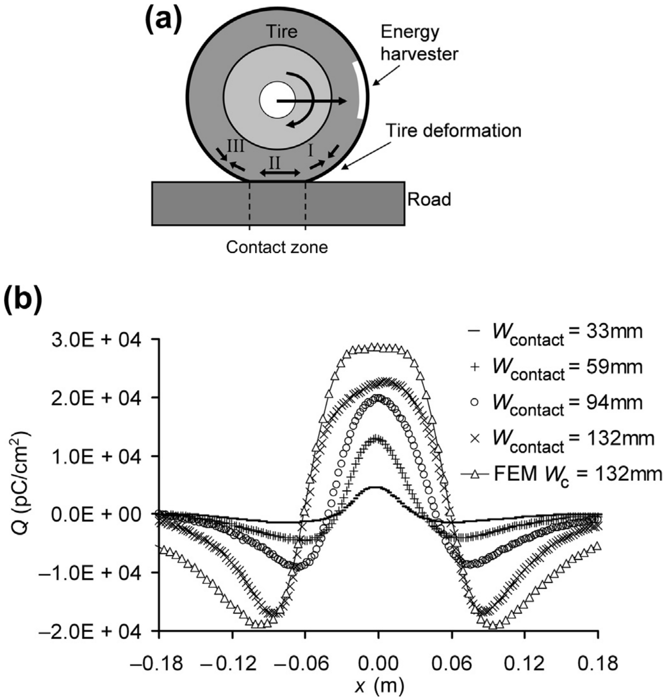

FIGURE 16.10

(a) Schematic diagram of the test setup for direct strain harvesting from a rolling tire. *Originally published in van den Ende et al., 2012b*. (b) Typical charge profiles for a structured PZT-polymer composite harvester strip as a function of the travel distance for different patch lengths. *Originally published in van den Ende et al., 2012b.*

lead to a power production of about 30 mW when cruising at a speed of 50 km/h. Such an energy production should be adequate to power a smart transmitter system capable of providing the electronic control system of future cars with relevant information on the state of the tires and their contact with the road surface.

CONCLUSIONS

PZT-polymer composites have always been seen as a means to bridge the gap in properties and processability between piezoelectric ceramics and piezoelectric polymers, yet have not been able to fulfill their potential. The conventional polymer-granular PZT composites are cheap but do not quite have attractive sensing properties and effectively no morphing potential. Structured 0-3 composites or quasi 1-3 composites in which the granular or rod-shaped piezoelectric ceramic particles are dielectrophoretically arranged in threadlike configurations offer a much better combination of properties, processability, and price. The structured composites offer great potential for diverse applications such as integrated switches and strain energy-harvesting devices as well as also other applications.

Acknowledgments

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CHAPTER 17

Biomimetic Materials

Julian F.V. Vincent

CONTENTS

Structures need stiff materials, fibers, space fillers, shock absorbers, tough materials resistant to wear, damage-tolerant materials, soft materials, and extensible materials. The work of Ashby on technical materials (Ashby, 2005), and of his student Ulrike Wegst on biological materials (Wegst and Ashby, 2004), allows comparison between technical and biological materials. When density is taken into account, biological materials (mainly made from two polymers—protein and polysaccharide—plus crystalline materials, mostly calcium based) are a match for technical materials (made from 300 polymers—not all very different—metals and ceramic). This versatility is highlighted by the range of properties of insect cuticle, covering a range of stiffness from 1 kPa (about the stiffness of thick mucus) to over 10 GPa in the mandibles of some plant-eating insects (Vincent and Wegst, 2004). This is a range of seven orders of magnitude, at a range of specific gravity going from a little more than 1.0 at the lowest end (such soft cuticles contain up to 70% water) to about 1.5 at the highest stiffness.

The main constituents are chitin and protein. Stiffness and strength can be varied in the usual ways for composite materials—varying the size, shape, and proportion of the different components and varying their distribution and orientation within the material. Biological materials are very different from artificial materials in that the different phases are matched down to the smallest detail. For instance, chitin nanofibers in insect cuticle have hydrogen bonding sites that are spaced such that they interact with specific silklike areas on the surrounding proteins. This makes for a very strong and precise bond that is not currently available in artificial composites.

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While water, as a plasticizer, is one way in which the stiffness of biological materials can be modulated (mostly used in animal tissues), another common way, used in plants, is to make the material cellular (Gibson, 2005). In animals with a stiff skeleton, the support material is concentrated either internally (chordates) or externally (arthropods), whereas in plants, the skeletal function is distributed throughout the structure as the walls of cavities that contain the cells of the plant. This is a very effective way of distributing material, and the cell wall is a fibrous composite of cellulose nanofibers in a rather heterogeneous matrix. The cell contents can disappear leaving empty cells as occurs in wood, one of the most efficient materials there is in terms of the multiples of its own weight that it can support.

The most difficult part of making a durable structure is joining materials. Biology gets over this in many ways with specific interfacial properties and gradient structures that match forces and displacements such that there are no dangerous stress concentrations that could start a fracture. This is achieved by precise control of interactions at the molecular level of structure.

MOLECULAR STRUCTURE

Liquid crystal structures have been observed at all stages in the development of organisms (Neville, 1993). It is at this level, with the organization at the molecular level that then becomes available, that the "perfection" and high performance of biological materials emerges. The mutual interactions and orientation of the molecules that liquid crystal structures provide ensure the controlled expression of the mechanical properties of those molecules. This allows very tight control over the interfaces between different materials and different structures.

Structures that could have been formed by liquid crystals have been observed in bone, plant cell walls, insect cuticle, collagen structures such as tendon, muscle, and many others. However, despite their apparent organization, if liquid crystals are allowed to organize without some sort of external direction they lack the coherence that would be required of a fiber or sheet—they become polydomain. It is likely that in order to be of mechanical significance as a membrane or fiber, they should be monodomain—that is, the orientation of the molecules or nanofibers (it can be either) has to be regular over a significant area. Ho Maewan has partially answered this, showing that, as with artificially produced liquid crystals, the birefringent structures of an embryo can be influenced, and perhaps even created, by small electrical fields (Ho et al., 1996). The implications of this approach are manifold, not least that it provides a bootstrapping mechanism for the initial organization of cells and tissues. Another answer to the problem was provided by Charles Neville who pointed out that the monodomain requirement could be achieved by templating (Neville, 1988). He called this constraining, in that he proposed the need for the cells secreting the liquid crystalline material to secrete a membrane.

The material is then secreted into the space beneath the membrane, being constrained between the membrane and the secretory cells. In the secretion of insect cuticle, this membrane is provided by the epicuticle that is secreted first, confining a constrained layer that is 90% water (the Schmidt layer) (Weis-Fogh and Neville, 1970). It is in this layer that the chitin/protein crystallites are orientated, being deposited (possibly driven by hydrophobic interactions between the proteins) on the inside of the

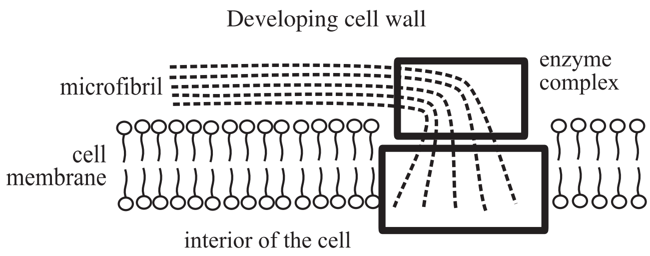

FIGURE 17.1
Cellulose production in a plant cell wall. Chitin production is probably similar.

epicuticle so that the constraining layer increases in thickness and becomes the cuticular exoskeleton. Mother of pearl (nacre) is laid down under similar conditions (Cartwright and Checa, 2007). In this case, the ordered framework is provided by chitin crystallites.

There is an opposing school of observations, fueled by observations on the synthesis of plant cell walls. Lurking, perhaps floating, in the cell membrane of plants are "rosettes" of enzymes producing multiple cellulose chains destined to become the microfibrils of the cell wall (Figure 17.1). These rosettes are constrained in their movement by microtubules just inside the cell membrane. The microtubules tend to impose their orientation on the orientation of cellulose microfibrils, which can be laid down in patterns that may not be immediately related to those observed in unconstrained liquid crystal systems (Lloyd and Wang, 2011). However, there is confusion about the relative importance of such direction over the tendency of cellulose to form structures independently. Certainly, suspensions of cellulose microfibrils are thixotropic, as are suspensions of chitin microfibrils, indicating that they are, independently, capable of generating stabilizing structures. Once gelled, the suspensions tend to lose water and precipitate, showing that the structures are themselves becoming more tightly bonded. It seems reasonable that there should be more than one mechanism for orientating cell wall components, since this makes the system more adaptive and reliable. So the final answer to orientation effects may be that they are facilitated in various ways, intrinsically and extrinsically. Certainly, the stiffness of the molecules (Figure 17.2) has a controlling effect.

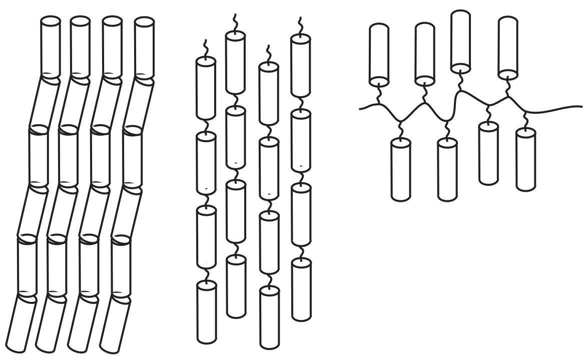

FIGURE 17.2
Shapes of some liquid crystal molecules. The cylinders represent stiff segments; single molecules are sufficiently stiff to form structures.

It is possible to make in vitro membranes that show liquid crystalline arrays. With collagen this has been shown to be dependent on concentration; the liquid crystalline structures will also form on a single surface without the need for additional constraint (Giraud-Guille et al., 2008). As the concentration of the collagen solution/suspension increases, the morphology of the self-organization of the collagen changes. The final sheet of orientated collagen, in twisted nematic form, can achieve this morphology remarkably quickly over a large distance (in the experimental apparatus used, this was a matter of centimeters) in the same way that crystallization can occur from a supersaturated solution of a salt, or ice can form in supercooled water. In each of the latter two analogs, a seed is required to initiate the process. A roughly similar set of stages of liquid crystalline structures has been observed in the spinneret of the nidamental gland of the dogfish (Knight et al., 1996). This gland produces a remarkable layered collagenous egg case (the "mermaid's purse" of the sea shore) from a serial arrangement of annular pits, each producing a single layer of the final structure with the collagen microfibrils in each layer orientated in a single direction; in the entire egg case the orientations vary from one layer to the next. The orientation of the microfibrils is strongly influenced by surface structures in the walls of the pit that orientate the microfibrils as they move past. The whole geometry of the secretory system is complex—the important message is that here is yet another collagenous liquid crystalline membrane, and that the process can not only be seen to be happening in stages in vivo, but can also be modeled, at least in principle, in vitro.

In passing, briefly but only because it is not contentious, the silks produced by spiders and insects have also been shown to be liquid crystalline, and it is possible to spin a high-performance fiber, sometimes stiffer than the biological original, from solubilized silk (Vollrath and Knight, 2001). Indeed, such materials are made and marketed commercially by Oxford Biomaterials Ltd. This is therefore a biomimetic material in terms of its processing, although the ultimate goal—to make silk from nonsilk proteins (for instance, from a sow's ear)—has not been reached. Ultimately, liquid crystalline structures are important in that they provide a pathway to maximize intermolecular interactions. For biological organisms, whose morphology is effectively "bootstrapped", liquid crystals provide the main, possibly the only, route to generating morphology (Ho, 1998).

MANIPULATING LIQUID CRYSTALS

It is apparent that the basic molecular unit of a biomimetic material should be a liquid crystal, more importantly a lyotropic liquid crystal. "Lyotropic" indicates that the molecule can be rendered unstable (i.e., plasticized) by the addition of a low-molecular mass solvent. In biological systems this is water, of course, but it does not have to be. But this does mean that the liquid crystal molecule can be intrinsically very rigid—so rigid that without the plasticizer it will not soften until the temperature is high enough nearly to degrade it. This description applies to most if not all biological proteins and polysaccharides. Indeed, without the plasticizer, such molecules could not exhibit liquid crystallinity. So we have a molecule that can self-assemble and then be solidified, all at ambient temperature, by modulating the amount of plasticizer. From a technical point of view this may be a problem, since the temperature at which the bonds are formed and the material is made is indicative of the energy of those bonds, hence the stability of the material in the presence of high temperatures and caustic chemicals. But that is the experience of technology; some biological materials are remarkably stable, such as the

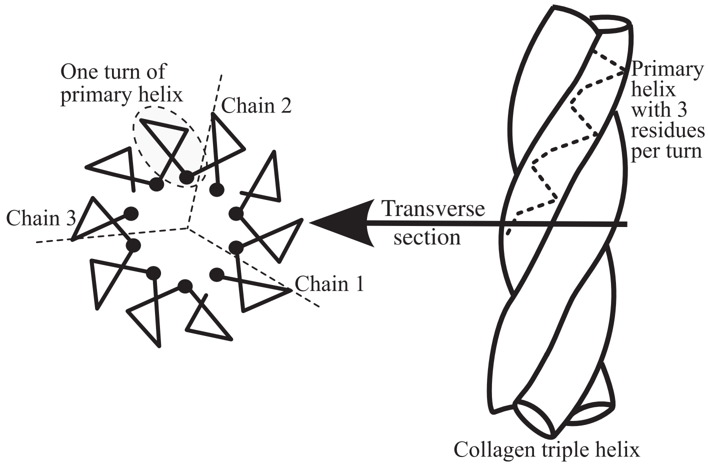

FIGURE 17.3

The primary helix, a single protein chain, is relatively floppy. Combined with two others it forms a much stiffer structure.

proteins found in the animals living around the "black smokers" where the sea floor opens out between the continental plates. Stability is conferred not by higher energy bonds so much as more of them—increased proline stabilizes the peptide backbone. Man-made liquid crystal fibers such as Kevlar are single stiff molecules relying on the stability of the bonds along the main chain and little else. This is in comparison with chitin, a polysaccharide which, with extensive H-bonding, forms crystals containing 19 chains packed into a fiber some 2.8 nm in diameter.

We look at the other biological liquid crystal fibers and see something remarkable (Figure 17.3). They all rely for their stiffness on inter- and intrachain bonding, being made of one (alpha-helical), three (collagen) or many (chitin, silk, cellulose, etc.) polypeptide or polysaccharide chains. This has a number of consequences:

1. the energy that is needed to make "difficult" bonds in man-made materials is replaced by extensive H-bonding—a lot cheaper in terms of energy;
2. there has to be a pre-self-assembly stage in which the stiff structure is generated. So the liquid crystalline structure finally produced is already two steps down the road of hierarchy, which brings greater stability and strength;
3. recycling is easier since the primary molecular bonds are at much lower energy levels than in man-made materials and so are more easily broken down;
4. the "extra" stage of assembly gives the material greater scope for variety of structures and interactions.

Doubtless there are more consequences, but these are enough for the moment.

Thus, biology is producing a material that can be a fiber or a sheet and has some of the regularity and precision of a crystal. Despite this regularity and stability, the material can be relatively easily remodeled and recycled, since the stability is a direct function of structure and extensive (but presumably relatively labile) hydrogen bonding, although there can be extensive covalent bonding emerging as the material "matures". This material can be used on its own since its degree of perfection gives it excellent mechanical properties. But it can also now be used as a template for further growth, either by accretion of further polymeric material or addition of ceramic material, usually a calcium salt or mixture of salts, commonly carbohydrate (calcite or aragonite) or hydrated phosphate (hydroxyapatite). The mechanisms by which the template works to direct the deposition of salts will not be discussed here—there is an abundant literature. The calcified structures can now reflect the organization of the template, which becomes the matrix within which the mineral is deposited. The mineral is not always "pure", in that in many instances (the shell of birds' eggs and of bivalve mollusks, the skeleton of echinoderms) the mineral phase is permeated by a small amount of organic material, often not enough to affect the apparent crystallinity, which changes the fracture properties to a more glassy mode, hence toughening the material. The molecular dimensions of the template direct the deposition of mineral in small particles that are, for reasons well understood in fracture mechanics, essentially unbreakable on account of their size.

Biological materials also excel at cellularity (Gibson, 2005). The mechanical design and properties of cellular materials have been extensively explored, including cancellous bone, wood, and cork. All the structures so far investigated have had all the cells the same size. Rod Lakes showed the advantages of a bimodal size distribution; a second-order honeycomb structure (i.e., a honeycomb in which there are some large holes), of the same weight per unit area as the first-order honeycomb is more than four times stronger in compression (Lakes, 1993); indeed the removal of material can improve energy absorption (Hepworth et al., 2002). Some biological tubes (feather rachis, porcupine quills, and hedgehog spines) are filled with foam that supports the wall of the tube against local buckling (Karam and Gibson, 1994; Vincent and Owers, 1986). Plants are the most advanced cellular materials, where the advantages of cellular structure are most apparent in the graded distribution of cellulose throughout a structure. In the flowering stem of the dandelion, *Taraxacum officinale*, the cells on the inside of the stem are about 60 μm in diameter with a wall thickness of about 1 μm. At the outer wall, they are 6 μm in diameter with a wall thickness of about 3 μm. This gives a gradient of about 1:25 in the cell wall volume fraction, which effectively increases the second moment of area of the column and greatly increases the efficiency of the structure (Vincent et al., 1992). Nearly all land plants show this adaptation to a greater or lesser extent, although as the cell wall is more lignified, the importance of gradation seems to become less.

HIERARCHY

Rod Lakes of the University of Wisconsin showed that the Eiffel tower is not only a level three hierarchical structure (it is made out of struts made from struts made from struts) but also 10 times more efficient in its use of material than the nearby Pompidou Centre. Olson reported the development of a "Terminator 3" "self-healing biomimetic, smart steel composite" in which he claimed that "a number of biomimetic concepts have been combined … [to give] … the reinforcement of a brittle ceramic by a rubbery polymeric component to provide 'crack bridge' toughening in which rubbery ligaments stretch across cracks" (Olson, 1997). Such ligaments were first reported in nacre (Jackson et al., 1988) and have since been found in other biological ceramics such as bone (Nalla et al., 2005) and sponge spicules (Mayer, 2011). The inclusion of rubber in ceramics, a direct analog, has a distinguished history.

Hierarchy in engineering materials and structures is therefore little explored, but a proper implementation could increase the efficiency (e.g., weight supported per unit weight of the support) and strength of a structure by several orders of magnitude with associated improvements in durability. So the next stage in making a material as efficient as biological ones is to introduce hierarchy. This has been studied and modeled in a number of systems, notably bone, which is constructed on a liquid crystalline collagenous substrate into which nanocrystals of hydroxyapatite are (somehow) interpolated. The nanocrystals are so small that they cannot contain a Griffith flaw and cannot therefore fail catastrophically (the same is true for the crystals in mother of pearl, although they are much larger, and the layers of silica in spicules of some sponges). Hierarchy maximizes the mechanical properties of the raw materials available, on the whole tending to make the material more durable.

Depending on the extent to which each level of the hierarchy is dependent on its lower levels, adaptation or optimization of the material is independently possible at each level of hierarchy (Fratzl and Weinkamer, 2007). Size differences between hierarchy levels tend to be a factor of about 10. A major advantage of hierarchical structuring is that the material can be made multifunctional (a strongly biomimetic characteristic) and that a specific material property, such as the fracture toughness, can be improved by optimization at different size levels. A direct consequence is increased adaptability of natural materials and increased range of properties of a single system (such as insect cuticle, bone, etc.).

ASSEMBLY AND MANUFACTURE

What are the most important characteristics of biological materials to feed into our own manufacturing techniques? What is there in the biological processes that we can direct, what can we emulate, what is necessary, where do we have to rely on intrinsic molecular properties in the way that biology does, and what aspects of the system are scalable and perform just as well at larger (and, probably, more easily implemented) sizes? From the engineering point of view, what properties do we want, what techniques and processes are available, what techniques would have to be developed, how much money are we prepared to spend, what is the advantage for which we can charge, and how expensive will the post-production and end-of-life (the engineering one, not ours) cleanup operations be?

Taking this list in reverse order, the environmental aspects must be paramount. Indeed a good part of the reasoning behind biomimetics is that it holds out the promise to be environmentally compatible. Assuming that the expenditure is sourced sustainably (all money comes from the sun directly, indirectly as oil or coal or environmental thermodynamic gradients, gravitational effects), life on this planet is sustainable only if we allow ourselves to be limited, or at least guided, by the irreducibles such as available space, energy, and mineral resource, all of them obtained without destruction of the plants and animals that, together, make this planet inhabitable. This is the heart of the biological system that has brought us this far and we have to respect it as the true and most secure basis of our continued existence. Sustainability has to be one of the main advantages of the biomimetic approach to technology.

One way of measuring this is to look at the importance of energy in materials processing (Vincent, 2008). In technology, about 75% of problems are solved by manipulating energy (increasing, decreasing, and resourcing), whereas the equivalent figure for biological systems is 5% (Figure 17.4).

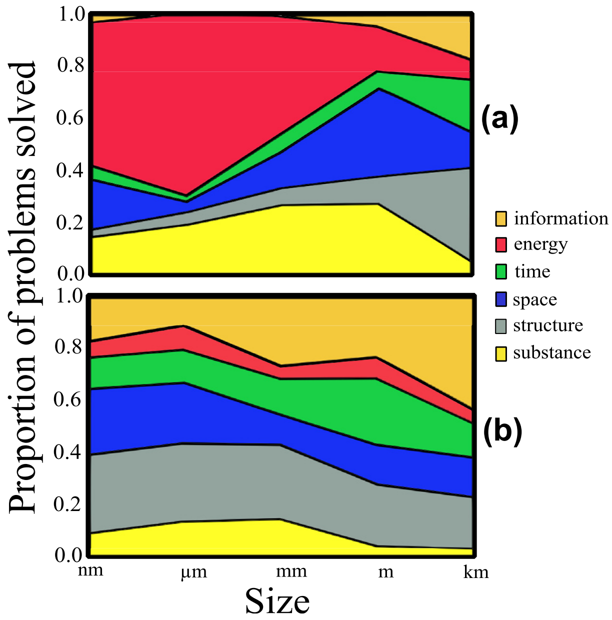

FIGURE 17.4

Comparison of problem solving in technology (a) and biology (b).

The replacement is from information and structure. The inference is that the structure is a product of the information (e.g., the design and physicochemical environment) of the molecules when they combine to form a material. In biological systems, the information comes from the molecules of inheritance—DNA—and is translated into the structural polymers—proteins and polysaccharides—which together construct the templates that give rise to the morphology and properties, physical and chemical, of the organism. From a technical point of view, there are difficulties with this approach: how to generate the required chemicals that will generate the shapes required, and the time and conditions required for those chemicals to interact with each other to form the required structures. Current technology mostly obliterates the information present at the molecular level. We need engineering techniques that can speed up assembly but make use of the intrinsic behavior of the chemicals involved. Current technology tends to regard the intrinsic properties of the materials as more of a nuisance to be subdued. The second main factor is that structure in biological systems is considerably more important than "substance", i.e., the input of raw materials. So with a combination of more directed assembly of carefully chosen molecules and the more careful generation of shapes using hierarchy, it is possible both to reduce the importance of energy and to facilitate recycling, since the range of input chemistries can be reduced.

The goal is a machine that can make a complex, multimaterial, multi "component" product of the sort we are used to calling an "'assembly". The product could be a kettle, a skateboard, a computer mouse, or an airplane, so it must be possible to make tough macro structures, moving parts, bearings, conductors, electronics, sensors, and actuators—all the functions (structures, systems, and "organs") found in typical consumer products. The search is therefore for shaping techniques that produce structure without further processing. This reduces the necessity for machining and molding, removing production stages, and speeding up production. Conventional examples are paper making and various fiber-handling techniques (knitting and weaving). More recently, three-dimensional printing (rapid prototyping or RP) has become possible. By analogy with the spinneret of the spider, it seems reasonable that extrusion-based RP could produce high-performance fibers in which the molecules are assembled at the time of production. This suggests that it is possible to produce fibrous composites with the orientations requisite for the structure. RP machines of whatever ilk mostly produce a layer at a time and the layers are all flat; this is for computational ease (and hence simplicity and reliability). It would be perfectly possible to bend and form the structure after it is been deposited—arthropods do the opposite (flattening a crinkled surface) in the later stages of ecdysis.

Most RP systems use only a single print head or mechanism, although they may make use of phase separation to produce small structures or controlled inhomogeneities. Although it is obviously possible to produce functionally graded structures by varying cell size, it would be nice to amplify the grading by controlling orientations or volume fractions of other components. Coextrusion would also be a possibility, extruding the fiber already in a matrix. An alternative approach is to use a water-based system where the materials either set on contact with (for example) calcium ions in a mass of water within which the object is being made, and/or use hydrophobic/hydrophilic interactions to self-assemble on a surface as they are extruded. This might require some postprocessing for the material to exude excess water, which is what insects do, but aquatic organisms use phosphorylation (caddis silk) or phenolics for their cross-linking and hydrophobicity (mussel byssus and a host of other, mostly protein, extracellular secretions).

BIOMIMETIC MATERIALS

There have been many prosthetic mimics of bone, skin, and other mammalian tissues. Few if any of these reproduce the mechanical properties of the tissues they replace or support, and even fewer use the material they are replacing as the molecular template for their design. This is probably because the tissues involved are soft and remarkably complex using liquid crystalline mechanisms that are available only at the molecular level. Only the simplest of biological materials have been mimicked successfully.

The most mimicked material is nacre, made of uniform platelets in regular layers. There are many ways of assembling platelets with a matrix of some sort but the majority involves very small-scale assembly or deposition and/or high energy and/or sophisticated materials and so are of little use in the larger world, although they might have applications at the micrometer level. Larger scale materials have had some success, most notably an example made from silicon carbide powder dispersed in polyvinyl acetate which was pressed into sheets 2 mm thick, rolled out until the plates were about 200 μm thick, and dried. Square plates, 50 mm on the side, were cut out from this and stacked up with graphite in between, which provided a weak, crack-stopping interface. This assembly was then pressed further and sintered under controlled conditions (Clegg et al., 1990). The resulting material had a work of fracture about three times greater than that of nacre but then silicon carbide is much stronger than the aragonite of nacre. Unfortunately, this material, although it has excellent mechanical properties, does pretty badly when it comes to recycling. A rather better candidate uses clay platelets in a polymeric matrix processed in the same way as paper (Walther et al., 2010). The platelets are covered in a cationic polymer; the valency of the ions can be varied, hence changing the properties of the matrix when the platelets are assembled. The resulting material has a high (0.7) volume fraction of clay platelets, but still not as high as nacre (0.95). However, it has outstanding stiffness and strength and is resistant to heat. Because the clay platelets are thin and well orientated, the material is also translucent. The latest research shows that the matrix of nacre is a lubricant rather than a glue, and the platelets are not uniform in thickness so that they jam up against each other when the nacre sheet is stretched and spread the load throughout the material (Barthelat et al., 2007; Espinosa et al., 2009). These are important characteristics, giving nacre its extreme toughness, and should be intrinsic to any artificial nacre. But the platelets have to match their deformities as they sit next to each other, so some sort of postprocessing is suggested in which the material, originally "perfect" and geometrically Cartesian, is abused so that it becomes randomly malformed.

The only successful model of wood is made up of helically wound tubes of fiber (glass and carbon were tried, but other fibers would do as well) in an epoxy matrix (again, other matrices could be tried). The target was to emulate the fracture toughness of wood, which until then (the early 1980s) was not understood. The model material was exceedingly tough in impact, easily better than wood with very high tolerance to damage (one of the characteristics of wood) (Gordon and Jeronimidis, 1980). As lightweight armor, it easily outperformed other materials when its density was taken into account. It has never been developed commercially, although methods of mass production have been developed, some of which use the technology of manufacture of corrugated cardboard (Chaplin et al., 1983).

Design criteria

The biomimetic materials may not fulfill sufficient design criteria for these to be acceptable for a particular project. This requires a rather more open approach. The criteria can be described in terms of property diagrams, placing the requirements within the property space that the diagrams provide. It is then possible to mix and match materials adjacent in the diagram, as described in several papers (Ashby, 2011; Ashby and Brechet, 2003). At the same time, analysis of the way in which organisms solve problems—the factors that seem to be taken into account—can be used to guide the design more toward the biomimetic goal (Vincent et al., 2006; Vincent, 2012). Thus, in addition to using characteristics such as hierarchy, composite structure, and gradient functions, organisms also take note of the following:

1. Compensation for low reliability of various functions. This implies feedback, which is a dynamic way of providing high-quality performance; it also implies shielding against failure in various ways, leading to good damage control and toughness.
2. Varying properties and shapes over small distances thus giving rise to multifunctionality.
3. Merging of functions and morphology (which is another means of generating multifunctionality and hierarchy). This is a useful exercise in the later stages of a design, combining characteristics to see how they can supplement each other (the functionality of a mobile phone is an exemplar) and reduce the number of components. This is sometimes called trimming.

4. Allow the material or structure to be more dynamic, relaxing the original design parameters so that the system can equilibrate to other energetic minima than may have been included in the original design.

All four of these principles overlap and, taken together with the principles discussed earlier in this chapter, provide a set of rules for designers of biomimetics materials and products.

CONCLUSIONS

Biomimetic materials offer higher structural performance for lower energy input and better recycling than technology does. We can obtain these advantages only if we understand how biological materials are constructed and are properly motivated to change the way we synthesize materials. We have some of the techniques available for the assembly of materials but currently lack means for generating significant amounts of the liquid crystalline structures that form the basis of biological materials. We can generate some rules or signposts for the design of biomimetic materials, notably hierarchy, composite materials, multifunctionality, dynamics and relaxation of parameters, and merging of functions.

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CHAPTER 18

Lightweight Materials, Lightweight Design?

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CONTENTS

Lightweight design can be defined as "the science and the art of making things—parts, products, structures—as light as possible, within constraints". It is usually reserved for things that need to be lightweight, yet still sufficiently strong and stiff to carry loads,[1] and it is this mechanical interpretation that will be the topic of this chapter. However, lightweight design can be generalized to apply to other needs also, such as the need to conduct a certain amount of electricity or heat at minimum weight. It is only for brevity that these nonmechanical interpretations are omitted here.

Let us analyze this definition. Lightweight design is a *science* because it is amendable to prediction based on theory and to objective verification by experiment, delivering reproducible results. We can, for instance, reliably predict that at equal weight, a solid square beam under bending made from aluminum will be 70% stiffer than one from steel, provided it has 1.7 times the steel beam's height and width. Simultaneously, lightweight design is an *art* because it requires intuition and creativity, in other words, a personal and subjective approach. We can, for instance, appreciate the efficiency of Antonio Gaudi's magnificent stone arches once we realize that these arches are shaped like cables hanging upside down: since free-hanging cables are loaded purely in tension, the stone arches must be loaded

[1] *Strength* is the ability to withstand loads without failure by breaking, buckling, or plastic (i.e., permanent) deformation, while *stiffness* is the ability to withstand loads without undue elastic deformation. In practice, design for sufficient stiffness is often more difficult to realize than design for sufficient strength.

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purely in compression, and since stone withstands compression very well, these "caternary arches" are remarkably strong for their weight. This explanation is easy enough, but it required Gaudi's intuition to make the creative leap from cable to arch in the first place, and then his unique genius to apply this principle to a stunningly effective upside down model of the Sagrada Familia's load-bearing structure. A contemporary example is set by aerospace pioneer Burt Rutan, who deliberately made the structure of his record-breaking Voyager airplane so simple that he could perform all the necessary calculations by hand.[2] The field of lightweight design is littered with similar examples that are easy to explain once the principle solutions are there, yet that utterly depends on insight, creativity, and genius to come into existence.

Returning to the definition, *constraints* are first and foremost the functional requirements of the thing in question. Removing, for instance, all safety equipment from an airplane obviously saves weight, but this is generally not a valid lightweight design strategy. Cost is also a functional constraint, often ruling out the application of certain lightweight but expensive materials; it limits the options for manufacture as well. Of course, what is affordable and what not varies from case to case: hand-crafted carbon fiber frames may be too expensive for everyday commuting, but well-affordable for professional racing. Second, there are constraints in the form of limited time, money, and resources available for the design process. In practice, many products are heavier than necessary simply because development time did not permit optimization. Legal requirements are a third constraint, with the bike once more providing an example: as we shall see later, the international federation of cyclists UCI demands bike frames to have a suboptimal shape. Certain materials may also be banned from products; for instance, in the 470 dual-handed Olympic sailing boats, carbon fiber is not allowed in the hull. Finally, our culture of use and product expectations may form constraints. If, for instance, the average user of a household kitchen step rated for 100 kg maximum (see Figure 18.4) expects it to hold 120 kg, then the design team had better take that higher value into account.

Why lightweight design matters is different from one "thing" to the next. A first category are motor vehicles: here, reducing weight can save energy and improve performance. For passenger cars, a 10% weight saving reduces fuel consumption by 5−7%, depending on type and use (Tempelman, 2011); in trucks, it saves 2−3% or may increase payload, although the latter applies only rarely (Tempelman, 2001). Portable products and all kinds of sports and leisure equipment are a second category. From briefcases to bicycles, the lighter they get, the easier they are to use. Less obvious, but very important, are disposable coffee cups, single-use packaging, and so on: products for which the material cost dominates the manufacturing cost. Lightweight design makes such products cheaper. Yet a fourth category consists of suspension bridges, skyscrapers, and similar structures for which the own weight determines how long or high they can be, and where weight reduction pushes back the boundaries of what is possible. In all four categories, lightweight design is common and often surprisingly refined. But beyond these four, there are good reasons as well: reducing weight is by itself a dematerialization strategy, decreasing the environmental burden associated with any product. Furthermore, it represents

[2]Rutan designed the Voyager to have a *statically determinate* airframe, which allowed him to dimension the individual frame members without a model of how the material deforms under load. Compared to so-called *statically indeterminate* frames, which do require such a material model for their analysis, this has one key drawback: if just one element fails, then the frame becomes a mechanism, collapsing immediately. Safety-critical structures, including airframes, are usually designed to be statically indeterminate, able to function even if one structural element fails.

a special challenge, worth pursuing for its own sake and for the surprising results, such as ultrathin lightweight chairs, it can deliver.

So, there are many good reasons to make "things"—essentially *anything*—lightweight. Yet lightweight design is perhaps more difficult than, and certainly quite different from, what many designers think. In particular, common "lightweight materials" (aluminum, composites, etc.) have a considerably more modest place within the field of lightweight design than what is commonly assumed, and applying such materials instead of, e.g., steel will give disappointing weight savings, at high cost. Below, this is explained in more detail. And as we shall see, when it finally comes to the materials, there are in fact surprising alternatives to the ones just mentioned.

SEVEN RULES FOR LIGHTWEIGHT DESIGN

This section presents seven design rules for lightweight parts, products, and structures. The inspiration comes from many sources and projects, but especially from these four individuals: Michael Ashby, James Gordon, Adriaan Beukers, and Claus Matteck. As usual for design rules, they should be used in conjunction with good design sense—not as a replacement for it. Furthermore, depending on context, certain rules may receive more emphasis than others; also, it will often be necessary to iterate between the rules during the design process.

Rule #1: do not overspecify

This is the most important rule for lightweight design. It is well known in design circles, perhaps phrased best by legendary aircraft designer Clarence L. "Kelly" Johnson, who stated: "Let the mission design the plane—not the other way around". In other words, the designer must always strive to ensure that the product does exactly what it needs to do, and nothing more.

For an example, think of an everyday product such as a household step (see Figure 18.1), to be designed for, say, the Japanese market. If we demand that all but the heaviest 10% of users should be able to safely use this product, then we should find the accompanying weight from the right ergonomic databases and use that value to derive our design target, or "limit load". If this means that the step may not perform as well elsewhere,[3] then so be it, but at least it will be optimal (i.e., light, cheap, and

FIGURE 18.1
Household step (injection-molded polypropylene).

[3]Germany comes to mind; indeed, the 90th percentile weight for Germans is ∼40% higher than that for Japanese.

ecofriendly) for its intended market—and Japan is large enough to allow for economies of scale. We should also specify and quantify what we mean by "able to safely use": how much weight can users be expected to carry in their hands, how much deflection is allowable before the step begins to feel unreliable, and so on. Exploring all possible scenarios of use is a time-consuming process, but it is the essential first step in lightweight design.

This rule may be well known, but overspecification happens extremely often[4]: think of the range of cars built by the VW group on the same platform, sharing many components among them. Such modular "product platform design" may be good for economy, but if it burdens the chassis of every normally powered VW Golf with the extra strength and weight required for those few GTI versions, then it is anything but lightweight design. In this light, one may wonder if the 1999 Audi A2 "supermini" owed its low weight not so much to its aluminum structure, but to the fact that unlike other midclass cars, it was a single-purpose design.

Rule #2: do not use factors of ignorance

A product that is exactly strong enough to carry the limit load will fail immediately once this limit is exceeded. Given that there are always uncertainties in design, production, and use, this situation must be avoided. So, the product must be stronger, leading to a ratio known as the safety factor. For aircraft, this factor generally is 1.5, meaning that an airframe will fail if the limit load is exceeded by 50% or more. This seems like a narrow margin, but it is sufficiently large to prevent nearly all overloading-related accidents, yet also sufficiently small to allow economical operation (the higher the safety factor, the heavier the airframe and hence the smaller the payload). For cars, the factor usually is two to three; for bridges, more like three to five. How high it should be for "non-safety-critical" products, such as the aforementioned step, is open to debate, and no single value can generally be given. Some designers then respond by using one they applied earlier to a comparable product (or worse, by making one up), but without proper referencing or research, this is not a safety factor: instead, we should call this a "factor of ignorance".

The difference between the two is that safety factors are based on a reliable body of facts. For aircraft, for instance, the heaviest loads they can encounter (the strongest gust of turbulence, the hardest landing, etc.) have been monitored for decades by the airworthiness authorities and indeed, increased when appropriate, so the limit loads are accurately known. The aircraft industry also knows the magnitude of possible errors inside its design and manufacturing processes, and this, together with the fact that aircraft operation is also tightly controlled, explains the small safety factor. For cars, bridges, and so on, the uncertainties may be bigger, but are also known.[5]

So, for "lightweight design of everyday things", one must determine the uncertainties in three key areas: the scenario of use, the materials and manufacturing (see also rule #4), and the design process (see also rule #6). Particularly, the first requires rigorous and time-consuming analysis, but in the absence of suitable authorities setting limit loads, this is the only way to avoid factors of ignorance and, instead, determine the proper factors of safety.

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[4]And not just in lightweight design; overspecification of tolerances, for instance, often makes products more expensive to manufacture than necessary.

[5]Airframes have to be fully tested before a plane can be certified for use. One particular and spectacular test involves bending the wing upward until it breaks. For bridges, the equivalent test is generally not available.

Incidentally, one typical kind of such factors concerns impact loads, or in terms of the step, someone jumping up and down on it. Designers frequently try and capture this scenario by multiplying the static load (i.e., user standing still on the step) with a certain "load factor" to arrive at the dynamic load (i.e., user jumping on it). However, unless based on relevant experience, this factor is just another factor of ignorance. With the advent of easy-to-use, reliable impact simulation software and high-speed video analysis of prototypes under impact, such uninformed design practice is no longer necessary, although in particular free-fall product drop impact still deserves much more research (Tempelman et al. 2012).

Rule #3: avoid bending and torsion

Assume we attach a beam to the wall on one end and load it with a force on the other (Figure 18.2). If we load it in tension, it will elongate a length u; if we load it in bending, it will deflect a distance δ. All else being equal, how large is the ratio δ/u? In other words, how much "worse" is bending as compared to tension?

For a solid, slender beam with a square cross-section, 10 times longer than high, engineering bending theory predicts a surprising ratio[6]: δ/u is no less than 400. For a more efficient, thin-walled hollow beam, the ratio is lower, but still around 240. Torsion is even worse: the ratio δ_{tor}/u is 1600 for a solid beam,[7] and around 950 for a more efficient hollow one. For strength-dominated design, the differences are less pronounced but still huge: a solid beam can carry around 60 times the same load in tension as in bending,[8] a hollow one around 40 times. Of course, these ratios are especially high for slender structures, but the message is clear: avoid bending and torsion by aiming for pure tension (or pure compression, as Gaudi did with his arches).

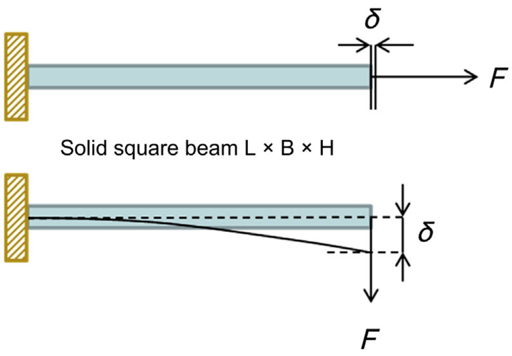

FIGURE 18.2
Simple beam in tension and bending.

[6]From engineering bending theory: $u = F \cdot L/(E \cdot A)$ and $\delta = F \cdot L^3/(3 \cdot E \cdot I)$. If the beam height is given as $0.1 \cdot L$, then $A = L^2 \cdot 10^{-2}$ and $I = {}^1/_{12} \cdot L^4 \cdot 10^{-4}$. Eliminating F, E, and L, we end up with $\delta/u = 400$.
[7]For torsion, we have $\varphi = M \cdot L/(G \cdot I_p)$, with φ being the angle of twist under torque M. In this comparison, M logically has to be equal to $F \cdot L$. Similarly, we obtain the deflection under torsion $\delta_{tor} = \varphi \cdot L$. With $G = 0.375 \cdot E$ and $I_p = 1/6 \cdot L^4 \cdot 10^{-4}$ we can again eliminate F, E, and L and end up with $\delta_{tor}/u = 1600$.
[8]In tension, stress $\sigma_{ten} = F/A$; in bending, stress $\sigma_{ben} = F \cdot L/W$, with $W = 1/6 \cdot L^3 \cdot 10^{-3}$. Eliminating F and L, we get $\sigma_{ben}/\sigma_{ten} = 60$.

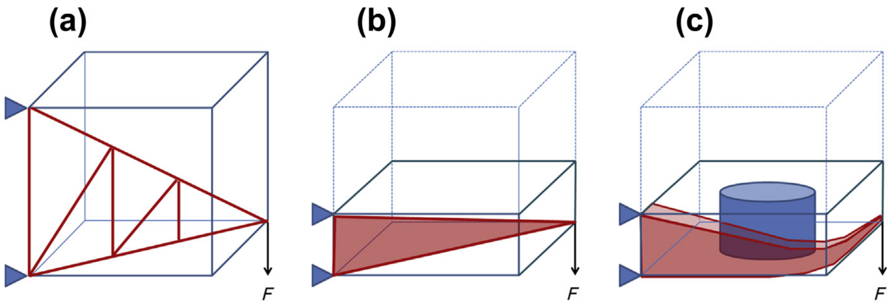

FIGURE 18.3
(a)—(c) How constraining the design space can cause bending and torsion.

A simple example shows how to do this, or rather, how *not* to do it. Imagine we have a certain cubical design space as shown in Figure 18.3(a), plus the objective to transfer the load F to the fixed world, at minimum weight, with a certain maximum allowable deformation. The result could then be a (seemingly old fashioned) truss structure, in which all members are either loaded in pure tension or in pure compression. Next, imagine that we flatten the design space—and with it, our structure—as in Figure 18.3(b). Now, bending becomes unavoidable. Finally, imagine we exclude a certain volume so that our structure has to go around it (Figure 18.3(c)). Now, torsion comes in also. The consequence is that our structure gets progressively heavier. This example may seem abstract, but is in fact derived from an existing product: a single-sided motorcycle wheel suspension arm (Figure 18.4). Choosing between steel and aluminum for this part may look like a lightweight design issue, but in reality much of the weight reduction potential has already been lost because of design space constraints.[9]

Finally, some advice for those who cannot avoid bending and torsion. The resistance to these two load cases depends on a geometrical property of the structure's cross-section known as the second moment of inertia, I. If we double the cross-section's width and height, then I increases 16 times, whereas its area (and, hence, its weight) only increases 4 times. So, it makes sense to use all the available design space,

FIGURE 18.4
"Mono-stay" motorcycle suspension arm.

[9]Do not throw away your monostay suspension arm just yet; it does have the benefit that the wheel can be removed more easily, among other things.

maximizing I. In terms of materials, this also implies that low density ρ is more important than high stiffness E, because it allows us to make large cross-sections without adding too much weight. And this, for the first time, brings us to materials.

Rule #4: do not select materials independent of shape and manufacturing methods

When "things" must be stiff and lightweight, one might expect we should make them from materials with a high ratio of their elastic modulus E over their density ρ. For things loaded in pure tension or compression, this E/ρ ratio is indeed decisive. Table 18.1 presents this so-called *indicator* for several "light" metals and composites, with low carbon steel being the baseline. Surprisingly, the metals all have comparable performance and only carbon fiber composites promise a weight reduction. However, for bending and torsion of beams, a different indicator applies: $\sqrt[2]{E/\rho}$. Now we see more differences, including the 70–73% stiffness increase for aluminum beams mentioned in the introduction. For plates and shells in bending and torsion there is another indicator: $\sqrt[3]{E/\rho}$, again with different performances between materials.

When strength matters, the indicator $\sigma_{\text{allow}}/\rho$ applies, with σ_{allow} being the allowable stress level in the material. Again, Table 18.1 presents some numbers, but these are not as generally applicable as those for stiffness; for instance, in case of fatigue (i.e., repeated loading), σ_{allow} gets lower, particularly for the light metals. And like E/ρ, this applies only to pure tension and compression. For bending of beams, the strength indicator is $\sigma_{\text{allow}}^{2/3}/\rho$; for bending of plates, it is $\sigma_{\text{allow}}^{1/2}/\rho$. Note, again, the differences between materials.

Now, consider manufacture. For three of the "usual suspects" in lightweight design, Table 18.2 presents the main manufacturing processes available for making beams and profiles (i.e., one-dimensional

Table 18.1 Material Indicators, Low Carbon Steel = 1 (Ashby, 2011; Beukers and Hinte, 1998)

	Stiffness Indicators			Strength Indicators		
Material	E/ρ	$\sqrt{E}/\rho$	$\sqrt[3]{E}/\rho$	$\sigma_{\text{allow}}/\rho$	$\sigma_{\text{allow}}^{2/3}/\rho$	$\sigma_{\text{allow}}^{1/2}/\rho$
High strength, low alloy (HSLA) steel	1	1	1	1.60–1.77	1.37–1.46	1.26–1.33
Aluminum (6061-T6)	1.00–1.02	1.70–1.73	2.03–2.06	2.15–2.23	2.38–2.43	2.51–2.54
Magnesium (AZ91-T6)	0.95–0.96	2.03–2.05	2.61–2.65	1.83–2.17	2.45–2.73	2.84–3.06
Glass fiber composite (E-glass fiber-polyester)*	0.75–0.86	1.82–1.92	2.41–2.51	5.54–8.57	5.08–6.86	4.88–11.8
Carbon fiber composite (T300-epoxy)*	2.98–3.08	4.04–4.08	4.42–4.52	16.1–25.1	11.1–15.2	9.21–11.8
Carbon fire composite (M40-epoxy)*	4.91–7.41	5.23–6.00	5.34–5.59	7.42–13.4	6.44–9.99	6.00–8.63

*Fiber volume 50%, continuous fibers, unidirectional lay-up (strength and stiffness in one direction only).

Table 18.2 Common Manufacturing Processes Per Shape and Material Combination

Material	Beams, Profiles (1D)	Plates, Shells (2D)	Free forms (3D)
Aluminum	Extrusion Roll forming	Blanking, bending, deep drawing, rubber forming, die pressing	Casting Forging Machining
Magnesium	Extrusion (–)	None	Casting (+) Forging Machining
Composites	Pultrusion	Autoclaving Resin transfer molding Filament winding thermoforming*	None
Stiffness indicator	$\sqrt[2]{E/\rho}$	$\sqrt[3]{E/\rho}$	$\sqrt[1]{E/\rho} = E/\rho$

(+) and (–): very well suited and not well suited, respectively.
*Composites with thermoplastic resins only.

shapes, or 1D), plates and shells (2D), and "free forms" (3D).[10] Aluminum appears as an all-rounder, with ample choices to make things of any shape. Magnesium, however, shows "gaps": its unavailability as sheet metal rules out 2D shapes, and 1D shapes are severely limited as well. Composites have a similar gap for 3D shapes. Of course, theoretically we can make nearly any shape out of any material, but in practice, certain combinations are prodigiously expensive and therefore effectively impossible.

One essential conclusion to draw from Table 18.2 is that shape cannot be selected independently of material and manufacturing process. Combining both tables underscores this conclusion in a less obvious, but more interesting way: for instance, if we reinforce a 2D shape with ribs, thereby turning it into a 3D shape, we eliminate bending as a failure mode (rule #3) and move from $\sqrt[3]{E/\rho}$ to E/ρ as the relevant stiffness ratio. Then, the materials do not perform as differently as before, when bending still was the main issue. Furthermore, we must take into account that certain processes introduce more material defects than others, reducing the σ_{allow} and forcing the designer to adjust safety factors (rule #2). Castings, to give one example, are effectively weaker than forgings.[11] In strength-dominated design, this dependency needs careful consideration, and underlines the importance of selecting shape, material, and process together.

Figure 18.5 shows how this works out for a common lightweight product, the bicycle frame. In aluminum, we most likely get a welded truss structure; in magnesium a one-piece, high-pressure die casting; and in composites a one-piece, thin-walled molded shell. There are of course alternatives: bike frames using extruded magnesium tubes have been built, and the UCI in fact requires composite frames to have four main tubes, ruling out the more efficient "plate design". And this does not yet include production volume: some of the methods in Table 18.2 are suited to small volumes, others to large ones.

[10] The distinction is subtle. For instance, plates and shells can be curved into three-dimensional shapes, but locally, they are still "2D" and, hence, likely to fail by bending or buckling.
[11] Unless casting takes place under vacuum to eliminate formation of brittle oxides. This "vacural" process, however, is very expensive.

FIGURE 18.5
"Standard" aluminum, cast magnesium, and molded composite bicycle frames.

Rule #5: do not use more joints than strictly necessary

After the complexities of the previous rule, this one is refreshingly simple: minimize the number of joints, regardless of type. There are two reasons why this reduces weight. First, as Figure 18.6 shows, joints may require a sizable overlap of material. Eliminating them removes this extra weight. Even the fasteners themselves can represent a significant gain: for instance, a midsized passenger car contains ~25 kg of nuts and bolts, or 2% of the car's weight.

Second, the joint reduces the strength and stiffness of the "thing" as a whole. Welded and riveted metal joints in particular are extra susceptible to fatigue and corrosion, reducing the allowable stress level. Structural stiffness can also be reduced: an example of this that the author worked on personally concerns a rollating walker, shown in Figure 18.7(a). The deflection of its handles under load (bending, *again*) was measured and, for modest loads, was found to be twice as high as predicted by a computer model that did not include the joints in this product (Figure 18.7(b)). Subsequent investigation showed that the walker's telescoping tubes, necessary to accommodate a range of user lengths, introduced considerable play and reduced the structural stiffness.[12] A true lightweight design, much in the spirit of rule #1, would not have such joints, but would instead be built to size (and, hopefully, avoid bending).

Incidentally, fewer joints not only means lower weight, but generally also lower cost. These two benefits can go hand in hand. And to show one of the (many) connections between these rules, certain manufacturing methods allow more integration of parts than others, so rule #5 is "joined" to rule #4.

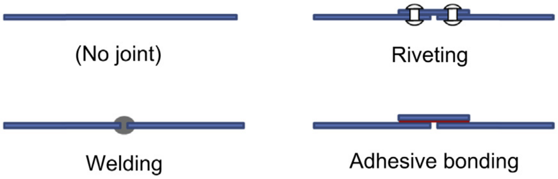

FIGURE 18.6
Joint types and material overlap.

[12]This was an expensive, high-quality walker with a "lightweight" aluminum frame.

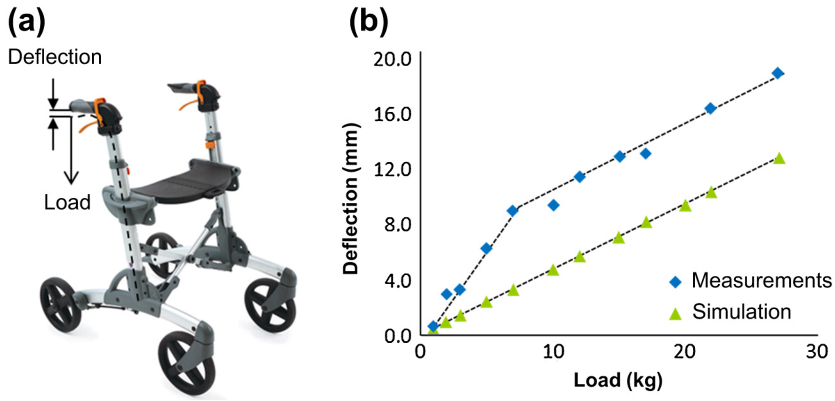

FIGURE 18.7
(a) Test setup of rollating walker. (b) Resulting graphs of deformation.

Rule #6: do not stop optimizing until the product cannot possibly be made any lighter

Again, an easy rule, but one that is often violated, mainly because optimization depends on detailed—read: costly and time consuming—prototyping and testing. Returning to the step example, imagine that the first production series is found to be too strong and stiff and can lose weight. Unfortunately, this would mean that a new mold has to be ordered for manufacture, and that is costly. Alternatively, one could optimize the design once the first mold has worn out and needs replacement anyway. By that time, understanding of how the product is used will have progressed (possibly adjusting the limit load), as will the knowledge of manufacturing-induced defects (possibly adjusting the safety factor), so that is the ideal occasion for redesign. Indeed, such optimization over the generations is common for high-value, high-volume products, such as cars and household appliances, but is not universal: too often, the attention of the original designers has shifted to other projects.

In fact, modern computer-aided design tools already facilitate optimization of the *first* generation to a degree unheard of just a decade ago. For a product like the step, strength, stiffness, impact, and even common manufacturing defects such as knit lines can all be optimized by a sufficiently persistent designer, using a standard laptop computer. Worthy of special mention are so-called "topological programs", which can automatically generate an optimal shape based on a specified design volume and external loads. Today, the output still needs manual postprocessing before it can be fed into other programs that evaluate strength or manufacturability, but such software will only get better in the years ahead.[13] Dutch designer Joris Laarman has applied this procedure to his "bone chair": note the tell-tale organic shapes that avoid stress-raising discontinuities.

Rule #7: do not rule out steel—not yet!

For the final rule, look at Figure 18.8, which shows the strain-to-failure of 10 types of sheet steel against their yield strength. High strain-to-failure implies that the material can be formed into complex 2D

[13]Of course, such shapes can also be "3D printed", hugely facilitating prototyping and manufacture.

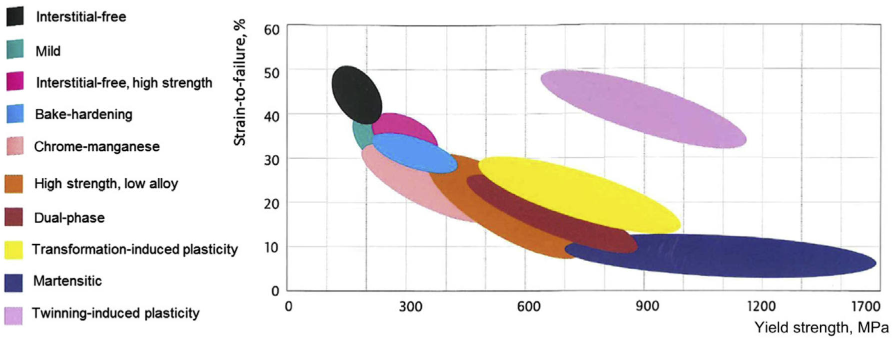

FIGURE 18.8
Strain-to-failure versus yield strength for steels.

shapes, whereas high yield strength means that the allowable stress can be high also. In particular, the so-called twinning-induced plasticity steels vastly outperform even strong aluminum alloys, which yield around 300 MPa (6000-series) or 400 MPa (7000-series) and have failure strains of around 20% maximum—assuming they are heat treated *after* forming, not before.

The conclusion is that if you want high-strength plates and shells, do not rule out steel too soon. And if you can avoid bending and torsion, this most versatile of all metals can even be attractive for stiffness-critical applications. The so-called hybrid molding process, in which a reinforced-plastic lattice structure is molded over and around a steel shell, is one way to do this. Granted, steel is virtually impossible to cast and difficult to machine, ruling out "3D shapes", but it can easily be shaped into profiles by roll forming (*not* by extrusion); alternatively, for "1D shapes" in tension, high-strength steel wire can be used, a fact exploited by another Dutchman, Frans de la Haye, in his "tensegrity bicycle" (Figure 18.9).

Steel's good properties notwithstanding, this seventh rule should in fact be rephrased as "do not assume that light metals and composites are all there is." Space does not permit full coverage of "unusual

FIGURE 18.9
Tensegrity bike frame. *Courtesy of Frans de la Haye.*

suspects", but worthy of mention are certainly bamboo for its astounding bending strength per unit weight (as proved by bamboo scaffolding reaching 10 stories high), and composites based on natural fibers. These natural materials are also relatively cheap and, unlike graphene, unobtainium or other "future stuff", available today. Sounds unlikely? Welcome to the surprising world of lightweight materials!

CONCLUSIONS

Lightweight design involves much more than the selection of "lightweight" materials, with particular proper specification of performance and safety (rules #1 and #2) being of greater influence on the eventual weight of the part, product, or structure than its material. Furthermore, material selection itself (rule #4) should be done together with selection of shape (see also rule #3) and manufacturing processes. Beyond that, joining and optimizing (rules #5 and #6) also offer good potential for weight reduction. Finally, designers should be ready to look beyond the well-known "lightweight" trio of aluminum, magnesium, and carbon fiber composites, and find unexpected alternatives, such as—but certainly not limited to—high-strength steels and natural materials.

Epilogue—the eighth rule

Even our best designs pale in comparison to the lightweight wonders of nature all around us. For instance, trees and bones are "manufactured" into complex shapes without a single stress concentration (Matteck, 1990), and these shapes "naturally" grow to avoid, in particular, torsion (Gordon, 1988). Nature also needs no energy-intensive materials, such as aluminum or carbon fiber composites, to produce these marvels. The consequence for lightweight design should be clear: be inspired by Nature, in other words, perform biomimicry. Perhaps this eighth rule should actually be the first.

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Interview with

Sam Hecht

WHAT ARE THE KEY ASPECTS AFFECTING YOUR MATERIAL CHOICES?

Companies present us with an opportunity or a problem and it's our job to creatively respond to it. Within that, we're not driven by materiality. Though, of course, materiality is vital. Materials are a way of being able to achieve an *idea* — finding the most appropriate material to achieve a functionality or presentation. Very rarely, we do run projects that are driven by *us*, rather than a company, and in those times it can sometimes be materially driven. So, for example, if a material fascinates us, we might explore what to do with it. But for most of what we do, we never start with a material. If there were a general sequence, I would say it's the idea, followed by material tied to manufacturing process. The exception is when we work with a company producing in a certain material; but that's seen as a virtue because they've become experts at it.

ARE ANY OF THESE ASPECTS DIFFERENT THAN 10–20 YEARS BACK?

We are involved with the same struggles that designers had twenty years ago. I don't think they are so radically different. Certainly there are many more materials available, and for some materials prices have reduced sufficiently that they're now feasible for us to use. Regarding production, for as long as I can remember, the 'China effect' has been a gradual process that in the last ten years has become turbo-charged. Products have become cheaper and cheaper. A product such as a kettle has become a commodity item: you can buy a kettle for under five pounds and it will last you for years. The commoditization of products such as kettles has also resulted in materiality becoming a differentiation factor for companies. But you'll find within that commoditization, companies are using techniques that are trying to faux materiality. So, they might present metal, but actually it's not metal. From my point of view, there's a problem because the reasoning is tied fundamentally to differentiation from competitors, rather than trying to improve the product. It's purely in the realms of the skill of the marketing person.

IF WE SAY 'MATERIALS & SUSTAINABILITY', ... ?

Our sense of sustainability is not really tied to material: it's tied to the product, its design, and its application, so that there is some kind of longevity. The product should last a reasonably long time and possess some value beyond its purchase. If we look at recycling, organized reclamation on a large scale by firms such as Herman Miller can be successful because their business model is based on supplying repeat customers: replacing old stock with new, returning it and reclaiming. Whereas in the vast world of commoditized goods, you don't know your customer and you've sold just *one* product. This requires an entirely different infrastructure to support recycling, which is where big problems occur. The reclamation structure needs to

BIOGRAPHY

Sam Hecht is co-founder of the design office Industrial Facility, alongside his partner Kim Colin. He has developed projects for companies ranging from Muji and Epson, to Herman Miller and Mattiazzi. His work has received over 40 international awards, including 5 IF Hannover Gold Awards, and is included in permanent collections of international museums.

Image Credit: © Industrial Facility

be as good as the manufacturing structure, and I think you can only solve it politically. To have much better product reclamation infrastructures will result in having to pay three times as much for a kettle. But if you can *avoid* having a product turn to waste, that's the best way. Designing a product for recycling is not the easy way out, it's hard. In some ways, Ebay is perhaps a far better recycling concept than designing something that is cheap but recyclable. I think we're always trying to put *less material* into products as a matter of course — that's an idea of being a designer, that's just naturally what we do. We like the idea of things that are only what they need to be.

WHAT ABOUT 'MATERIALS & TECHNOLOGY' ...?

Most smart materials are inaccessible and specialized. They are in the realms of the space industry, defence, medical - they're just not possible to involve in our projects. The barrier also comes down to cost. But when these technologies are made accessible, demand will undoubtedly increase. For example, last week I bought a jacket from Uniqlo. It has a superior coating where water just globules and comes off; it has a special stretched polymer and down insulation, making the insulation stretchable; and it has a method of keeping in heat but preventing sweating. All of those things are unbelievable technologies, made possible because of Uniqlo's method of mass manufacture. On another matter, I think 3D printing and DIY design are incredibly exciting and will 'take off' some day. But currently, with 3D printing, there is no measure of quality. It's messy and the resolution is poor. The people who are in that world think that it's just incredible; the people who are outside that world think, 'well, it's just like a naff piece of rubbish quickly made'. So there's no equilibrium yet. To the person on the street, a 3D printer is not going to result in the kinds of things you can get in a shop. But I think its improvement and widespread adoption is inevitable - just like the ink printing industry.

MATERIALS & USER INTERACTION...?

This is important. A material must be appropriate to the function of a product. Not only that; qualities such as the material finish, its softness or its hardness are the sorts of things we try to take care of and lead on. These are things generally not answered by companies. Materiality relates to the senses, which we use to figure out whether something is going to be pleasing to us or not. Just like food really. For myself, whenever I'm looking at objects, I generally pick them up, press them, feel them and smell them. This way I get some kind of experiential feedback from the material. Done properly, you're really anticipating the experience of use for a product. So even when we do a toilet brush, it's a hard gloss plastic that's easy to clean and resists dirt collecting. Clients don't even *think* about the toilet brush at that depth. It's not their *thing*. That's why they're asking a designer. Marketing people would say that materials are a way of 'drawing people in' to a product. In their opinion, the measure of product success is if it has been bought. But as a designer, you can get into sticky ground taking the approach that product success is related to catching people's eye. Once a product has been bought, you don't need to catch that person's eye anymore. And yet a product is catching a person's eye every day they come into contact with it. So in some ways, finishes — if they are faux — are completely and utterly pointless once you've bought a product. Unfortunately there are many cases where designers play with the rationality of materials, and they get it wrong and it just doesn't work. You get uneasy about such products, and you might not know why. That's why we pay a lot of attention to the perception of what people have about the object that they're using. And then that informs which material, finish and colour is appropriate.

FROM WHERE DO YOU GET INSPIRATION AND INFORMATION FOR YOUR MATERIAL CHOICES?

We have our own materials library, used often as a form of proof to a client or a company, to show that something exists. Over the course of a year, I collect materials that have intrigued me, or which a client company – such as Muji or Herman Miller – has shown me. They are cut down to the size of a CD and put into an index system. We rarely collect products from their material standpoint. Mostly it's actual material samples. When companies present us with materials, we're relying on their own internal research and investigation to make suggestions to us. If we consider the experiential side of materials, the decision-making is all *intuitive*. Intuition leads to a conversation: 'what do you think about this?', 'is this working?'. The answers can be 'I'm not so sure I like black, because it seems so serious'; or 'it's just too hard'; or 'well, that's interesting because it's just so different to the other ones, and there's a good reason for that'. The problem with design is that there's no right or wrong. The only way you can push your idea through is if you have a mechanism to explain it. Clients can share intuition, but they don't have to understand why.

HOW DO YOU THINK MATERIALS SHOULD BE TAUGHT IN DESIGN EDUCATION?

I've taught for many years. I teach about ideas, products and the relationships they have to the world and to people. It's up to the students if they see material as part of their creative process for realizing an idea, or if a material is presented to them and they see potential for its use in their work.

IF4000 Knives

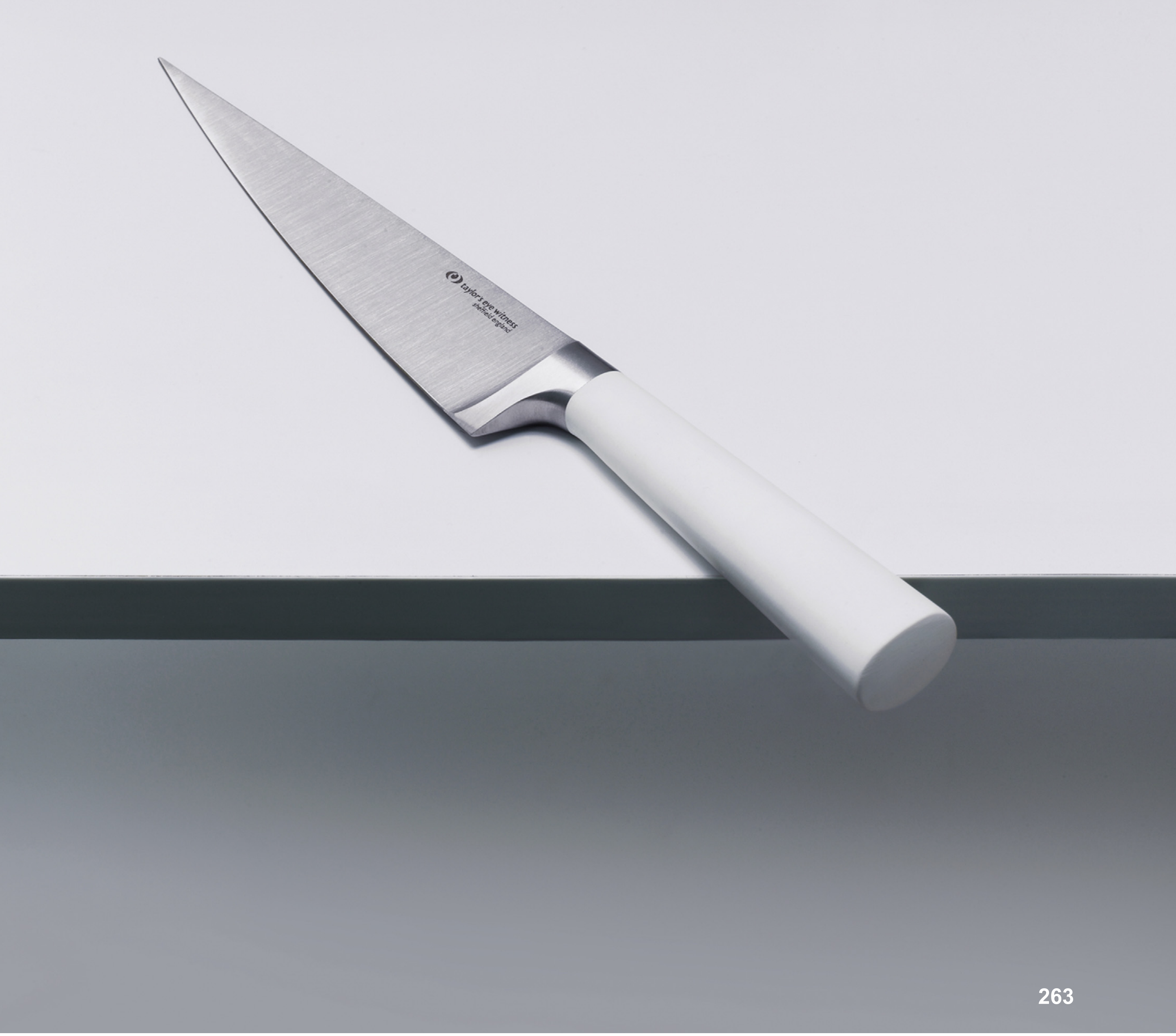
Client: Taylor's Eye Witness

Year: 2004

Product Material(s): Precision-forged and ground stainless steel blade with polyester and melamine composite handle

Brief Description: A simple tapered oval form is used for the handle, which means that even with the eyes closed, the user knows which way the handle is facing. The polyester and melamine composite is cool to the touch, bringing a better sense of presence and grip than comparatively warm thermoplastics.

Image Credit: © Angela Moore



Cutlery

Client: Taylor's Eye Witness

Year: 2007

Product Material(s): Stainless steel

Brief Description: Cheap disposable plastic cutlery sold in supermarkets sometimes tries to present itself as mimicking the grandiose of handcrafted metal cutlery. In this project, the vernacular of plain disposable plastic cutlery was turned into a metal counterpart. The four-piece set includes a spork (combination of a spoon and fork).

Image Credit: © Industrial Facility

Branca Chair

Client: Mattiazzi

Year: 2010

Product Material(s): Handcrafted and CNC machined wood in ash, beech and oak

Brief Description: This project intended to push Mattiazzi technologically into the position of the robotic craftsmen, creating a chair whose ingredients are a combination of highly complex parts alongside traditional shaping and finishing by hand. The branches of a tree that turn, twist, meet and branch off provided the critical analogy.

Image Credit: © Industrial Facility

Flexlamp

Client: Droog

Year: 2003

Product Material(s): One-piece silicone soft molding

Brief Description: Flexlamp regards the engineered fluorescent bulb as no more than a filament, and in so doing, provides a union between this filament and a lighting shade. The project required considerable material and technical leaps: the shade is dramatically flexible, able to slip over a fluorescent bulb.

Image Credit: © Industrial Facility

Interview with
Alberto Meda

WHAT ARE THE KEY ASPECTS AFFECTING YOUR MATERIAL CHOICES?

With the *Light Light* chair experience, I realized that there is an important aesthetic of reduction. With the *Jack Lamp* (Luceplan), I noted the need for light constructive solutions coherent with the immaterial side of light. So I usually start with a constructive idea and I do not have a fixed repertory of forms. During the design process I try to formalize the idea, holding on to a physicality of a material or a process. The form does not exist at the beginning; it reveals itself on the way. It is often a suggestion of the structural or technical operation or process to trigger the thought of an object. Unknowingly, researching and drawing for an 'elegant' solution, I arrive to its shape.

I always try to use contemporary materials and processes, such as plastics or melted metals, which enable the integration of functions and then the reduction of components.

My attempt at simplification is confirmed by the possibilities of the techniques used from time to time. The aim is to obtain objects with a simple aspect, a unitary image, 'almost organic', because my focus is not 'a priori' on the shape, but on the relationship between the components and between the objects and the users.

The contact with the scientific and technological context is important because it affects the idea's formalization and its translation into a product. Materials and processes represent the range of opportunities that can evolve. It may seem a paradox but I think that the more the technology is complex, the more it is able to produce simple and unitary objects, 'almost organic'.

ARE ANY OF THESE ASPECTS DIFFERENT THAN 10–20 YEARS BACK?

Once the material was an 'a priori', but today it is different because you can create tailor-made materials. It definitely affects the conditions and criteria by which to select materials. Moreover today, through continuous technological progress, the industrial design field is oriented to the invention of the process itself. In my opinion it is as if the designer comes back to his or her origins as a craftsperson, and can have a direct participation in the creation: building machines to process and create objects or components. Some young designers are doing it with 3D printing and laser cutting, by which part of the design process becomes inherent to the production process. This is the biggest change I have seen in recent years that could also affect the future.

IF WE SAY 'MATERIALS & SUSTAINABILITY', ... ?

I always tried to create lasting objects, designed to survive the passing of the years because they are made with the spirit of solving a simple problem, rather than chasing the latest fashions. I think that my objects in many cases are sustainable because I always tried to use the appropriate material.

BIOGRAPHY

Alberto Meda studied mechanical engineering at the Politecnico di Milano. He worked as technical director, responsible for the product development, labware and furniture divisions for Kartell. As a freelance designer, he worked for companies including Alias, Alessi, Cinelli, Colombo design, Ideal Standard, Luceplan, Legrand, Mandarina Duck, Omron Japan, Philips, Olivetti and Vitra. He also served as a project consultant for Alfa Romeo. Meda is a docent at the *Domus Academy*, at the Politecnico di Milano, and at the *University IUAV* of Venice. Some of his products form part of the permanent collection at the Museum of Modern Art of Toyama and The Museum of Modern Art in New York.

Image Credit: © Miro Zagnoli
(www.mirozagnoli.it)

Today environmental awareness has increased; perhaps I would change some of the choices I made in the past and try to focus more on using one material for the whole object.

For example, the *Lola Lamp*, a project of 1987, was made from different materials and technologies, adapted to its different properties to solve constructively the various components. The fork-head was made in polyester with fiberglass; the stem in carbon fiber; and the base in zamak and coated polyurethane. The parts are glued together with epoxy resins. Despite its large number of materials, the Lola's image is unitary. Maybe today you could imagine a different solution, with snap assembly to facilitate the disassembling.

WHAT ABOUT 'MATERIALS & TECHNOLOGY' ...?

Technological aspects are the main themes of my design. For example, the *Frame* project is made up of various models (Highframe, Armframe, Longframe, Floatingframe and Rollingframe), all derived from the same construction idea: correlating a structure of extruded and die-cast aluminium elements, and a seat made with a PVC-coated polyester net with a few screws. I researched for a certain visual lightness related to the need to give continuity to the shape whilst concealing the joints. The extruded element, common to all models, is designed to accommodate the fabric that functions as a seat, inserted in a groove, and to connect it smoothly to the die-cast elements. The meeting of these two technologies of aluminum — extrusion and die casting — is made in such a way as to obtain a unitary and continuous structure, where the junction nodes are integrated and natural.

MATERIALS & USER INTERACTION...?

We must pay attention to sensory aspects of the different materials, because we are used to using all our senses to judge the quality of a product. The user interaction is based on feelings that the materials convey and it should be based on the function of the object or component. For example, the armrest of a chair being cold or hot depending on whether it is made from aluminum or polyurethane.

FROM WHERE DO YOU GET INSPIRATION AND INFORMATION FOR YOUR MATERIAL CHOICES?

In the 1970s there was big excitement around plastics. Internationally a lot of fairs were organized with the aim to know the characteristics of new polymers and show their opportunities of application. It was very helpful to look at the applications of these materials in different fields and to take inspiration from that into the context of product design. My job experiences with Alfa Romeo helped me to expand my skills and knowledge on materials and technologies. At that time, I began a collaboration and experimentation with Alias that still exists. I was very lucky to find a sensitive and curious partner available to accept the risk to explore new territories. For example, I proposed to them an experimental research on composite materials technology with the aim to verify the possibilities of use in domestic items. Thus *Light Light* was born (1984), a chair made of carbon fibre. Composites are usually reserved for more sophisticated applications, such as the aeronautic field where it is necessary to make resistant and lightweight products. The chair was an opportunity to test the structural performance of these anisotropic materials in a structure that is stressed directly from the user's weight. The project research allowed me to understand many things about the choice of materials and techniques, and to explore beyond physical lightness into the value of 'visual' lightness.

HOW DO YOU THINK MATERIALS SHOULD BE TAUGHT IN DESIGN EDUCATION?

I think there is a need for a substantial and basic education focusing on the fundamental properties of different materials and their mechanical, thermal and electrical characteristics. It is also important to have knowledge of basic principles of structural engineering. It is important that the designer knows why things stand, what is the elastic modulus of each material and to have also some scientific criterion in the selection. This gives more assurance that the material chosen to fulfill its function is correct.

Moreover, during its formation, the designer should have an overall experience of the various materials classified according to their most significant applications, so that it is easier to locate and also intuitively consider what is the most suitable material.

Through curiosity and analysis of things around us, we can learn many things and the pleasure of discovering and understanding the intelligence contained in objects is a very strong stimulus to learning. What you learn in this way is difficult to forget. The solutions are stored and will one day be used and/or reinterpreted in unexpected ways.

I believe it is not necessary for the designers to have expertise in the field at a micro-level, but they need to be able to relate and communicate with professionals, experts from various fields and to be able to make use of various skills from time to time as the project may require.

Otto Watt

Client: Luceplan (www.luceplan.com)

Year: 2011

Designer: Alberto Meda + Paolo Rizzatto

Product Material(s): Aluminum

Brief Description: A desk lamp designed from a LED source that consumes only 8 Watts but illuminates as much as a 35 Watt halogen lamp. This allows a drastic reduction of energy consumption. The project focus was to reduce the amount of material used, the volumes and the formal complexity, aiming to obtain an object with minimum visual impact. In order to facilitate recycling, the lamp is manufactured from a single material: cast aluminum for the arms and pressure injected aluminium for the head, articulations and base.

Image Credit: © Ivan Sarfatti

Light Light

Client: Alias (www.aliasdesign.it)

Year: 1984

Product Material(s): Composites

Brief Description: The idea of this chair came from experimental research on the technology of composites to test their potential use in the home environment. These composites, comprising a sandwich with a honeycomb core of Nomex — a special type of polyamide and unidirectional carbon fabric coverings — are usually utilized to make strong, light components for the aerospace and racing sectors. The objective of lightness, to reveal structural performance, means reducing the sections to a minimum, by working with 'subtraction'. The resulting form is not governed by a predetermined language, but by the aim of investigating the limits of what is possible.

Image Credit: © Roberto Sellitto

Solar Bottle

Client: not yet commercialized

Year: 2006

Designer: Alberto Meda + Francisco Gomez Paz

Product Material(s): PET

Brief Description: Solar Bottle is a low-cost container capable of disinfecting water for those populations who consume microbiologically contaminated raw water. It is based in the SODIS (Solar Water Disinfection) system. The PET container has a dual face: a transparent face for maximal collection of UV-A rays and an aluminum face that absorbs the sun's infrared rays, increasing the temperature and improving disinfection. The reduced thickness assists transportation and storage. The handle integrates the angular regulation needed to improve sun exposure depending on which latitude of the world the process is executed.

Image Credit: © Alberto Meda

Meda Morph

Client: Vitra (www.vitra.com)

Year: 2006

Product Material(s): Steel, Aluminum (crossbars and legs)

Brief Description: This project comprises a series of individual tables, a conferencing system and a folding table, so that different requirements can be fulfilled with a single, highly versatile product line. The MedaMorph system consists of 4 elements: two types of leg, a star connector and cross bars of variable length. The crossbars and legs of MedaMorph are manufactured from steel and die-cast aluminum. The spider mounts are also made of die-cast aluminum. Table tops are provided in natural wood veneer, a melamine finish or powder coated.

Image Credit: © Vitra

SECTION 4

Proficiency in Materials

This section elaborates on the practical task of selecting one material over another. The contributing authors discuss functionality and expression, ways of learning material properties, and experiential-based materials selection.

CHAPTER 19

Materials Driven Design

Aart van Bezooyen
Material Stories

CONTENTS

Materials define the physical world we live in and form the base of all things we can see, touch, hear, smell, and taste. Imagining a world without materials could be considered as floating in a big room of darkness and silence that would keep us from any sensorial experiences. A kind of scary dream don't you think? Luckily, our world is full of different woods, metals, plastics, glasses, and ceramics that fill our daily lives with continuous flow of sensory interactions.

Imagine waking up covered in cotton blankets and washing your face in a ceramic sink where you also find your plastic toothbrush. When you get in the kitchen, you cut some bread on a bamboo board and fill tap water in a metal pot to heat your first cup of coffee. At the wooden table, you open a plastic bag with cereals and fill a porcelain bowl with milk. With your other hand, you hold today's recycled newspaper. In other words, if we start looking closer at our daily life we realize the enormous diversity of materials that touch our day.

Designers have a very big responsibility because with new products they are developing the future experiences and interactions of our everyday lives. Victor Papanek (1971) even says: "In this age of mass production when everything must be planned and designed, design has become the most powerful tool with which man shapes his tools and environments and by extension, society and

Materials Experience. http://dx.doi.org/10.1016/B978-0-08-099359-1.00019-9

himself". It is important to realize that with every product we design we are shaping the experiences and lives of hundreds or even thousands of people, which makes it very important to consider how and why we are making things. Because materials play a key role in the experience of products, designers are challenged to appropriately use materials in everything they create. This might sound obvious but the time pressure in design projects and condensed educational programs are minimizing time for materials. How come?

MATERIALS IN THE DESIGN PROCESS

That materials play a fundamental role in the design process is clearly demonstrated in the educational model of the Bauhaus (1922), a school in Germany founded by Walter Gropius that combined crafts and the fine arts, which operated from 1919 to 1933 (Figure 19.1). Not only do materials play a central part of the educational program, but also the range and combinations of materials such as wood, metal, fabric, color, glass, clay, and stone are very essential. For more information about this diagram and the Bauhaus approach to education, please see "Teaching at the Bauhaus" by Rainer Wick (Wick, 1999). Unfortunately, the Bauhaus educational model is a historical model and not a universal reference for the status quo of materials in education. To discuss today's role of materials, we have to look at the change a single product brought us, the computer.

The rapid growth of computer aided design (CAD) tools since the 1980s changed the design process and the role of using materials in design; American graphic designer Milton Glaser even said: "Computers are to design as microwaves are to cooking". I do not see computers as enemies of design, although their introduction into the academic system has changed a lot in the way design is taught, practiced, and perceived. The introduction of computers in the design process gave way to a previously unknown dimension of immaterial prototyping in a virtual world. With the help of computers, we are able to design and develop products in a very visual way without getting our hands dirty. Surely, CAD tools make it possible to speed up the process of design but on the other hand they are very form and

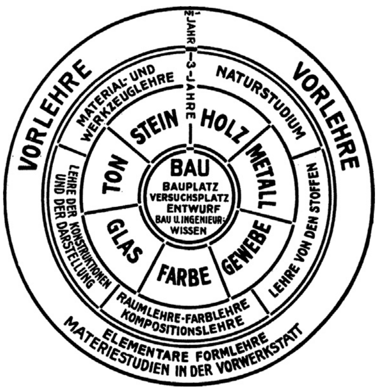


FIGURE 19.1
Diagram for the structure of teaching at the Bauhaus (1922).

function based and give little credit to the aspect of materiality in design. In most programs, materials are no more than a library of skins or patterns that can be changed with a single click. This way of selecting materials comes very close to pure aesthetic changes, also called "styling". Virtual design methods that are far from reality are leading to a group of design students with little, or no, understanding of materials. Keeping in touch with materials is also about keeping in touch with reality to make products for a real world.

First, there is the reality of the making. (1) Besides the differences in quality, cost, and availability of materials, manufacturing often plays a crucial role. For instance, titanium is a wonderful material that combines superior strength with lightness but it is difficult to process due to the damaging of processing tools. Second, there is the reality of the user. (2) Through iterative steps of making, testing, and evaluating tangible prototypes, it is possible to involve the user (experience) from the start of the design process. Finally, there is the reality of the object. (3) Subtle use of materials is of high importance to create a strong product appearance. Especially in the field of automotive design we see how colors, textures, and materials are orchestrated into an interior harmony. Not caring about materials in education and ignoring these "realities" will lead to the design of products that are impossible to manufacture, serve nobody's needs, and provide no aesthetic pleasure.

RELATIONSHIP BETWEEN MATERIALS AND DESIGNERS

For designers, it is important to learn about materials. To know what materials are, which qualities they have, how they are sourced, and how they are processed. Keeping track of new developments in materials and manufacturing techniques is an important part of the design process. In the context of materials selection, you cannot select what you do not know. History shows that new forms and aesthetics are the result of the use of a new or unused material, while in other instances the material or manufacturing process is developed to realize the designers' ideas. In other words, it is important to see that materials and design develop together.

The designer's relationship with materials has evolved dramatically mainly due to the introduction of new materials and processes that provided them a greater creative freedom. For instance, Andersen's Armchair, constructed from a blob of brown polyurethane foam, has become a symbol for material experimentation throughout the 1960s. Similarly, Marcel Wanders's Knotted Chair (1996) uses knotted aramid-based fibers that are frozen with epoxy resin into the shape of a low chair (Figure 19.2).

Today, plastics can be as transparent as glass, as flexible as fiber, as metallic as aluminum. Metals are being replaced by ceramics and sheet metal by carbon and glass fibers. This new and changeable character of materials has generated new forms and a more experimental approach toward design. This experimental approach created a new relationship between designers and the materials they use, a relationship that has the characteristics of research where new materials and technologies are being explored. As Professor Mike Ashby (1992) said: "The successful designer has escaped from the mentality associated with previous generation of materials, and has exploited the special properties and design freedom of the new ones".

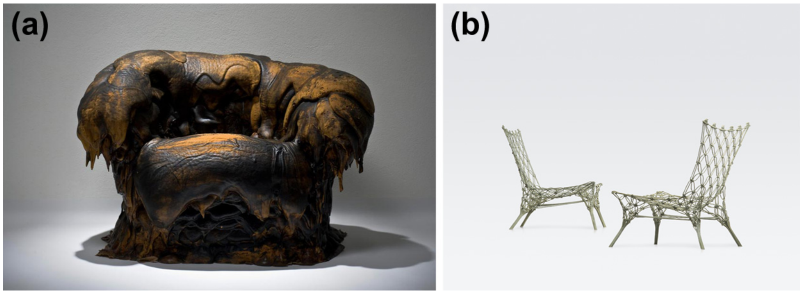


FIGURE 19.2
(a) Armchair by Gunnar Andersen (1964); (b) Knotted Chair by Marcel Wanders (1996).

The growth of education and commercial material libraries during the last decade demonstrate that the interest in new materials and technologies is a still growing process. Also, the dialogue between designers and industry is getting more widespread and special awards and competitions, often by the industry, are inviting designers to explore the new possibilities that materials and technologies have to offer. The Dutch DOEN | Materiaalprijs, founded in 2008, is a good example of accrediting designers with a yearly award for innovative and sustainable use of materials.

Kirstie van Noort's project is a good example (Figure 19.3). Curious about the origin and production of china, she spent 2 weeks in Cornwall in the United Kingdom, which played an important role in the industrial revolution. Until the 1990s, there were dozens of mines from which copper, tin, and silver were extracted but when the prices of the materials dropped, all mines were forced to close down. The remaining mines with piles of raw materials that have been discarded by the industry create a color pattern in the landscape. By treating materials as paint and using them to color earthenware and china, she developed a color chart with 108 different colors. Each color referred to the richness of the landscape in which they were once flourishing industries.

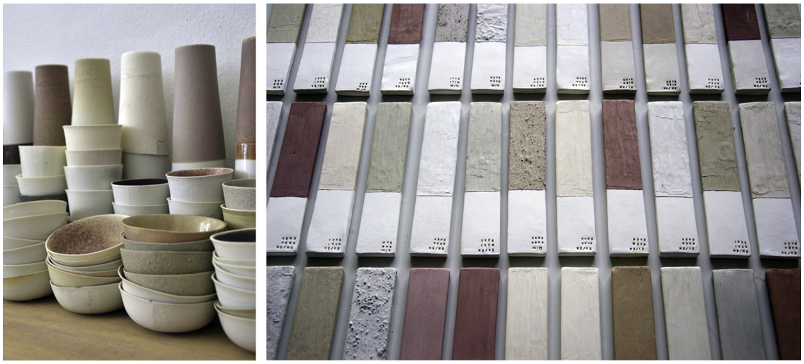


FIGURE 19.3
Tableware made of porcelain production residues by Kirstie van Noort (2012).

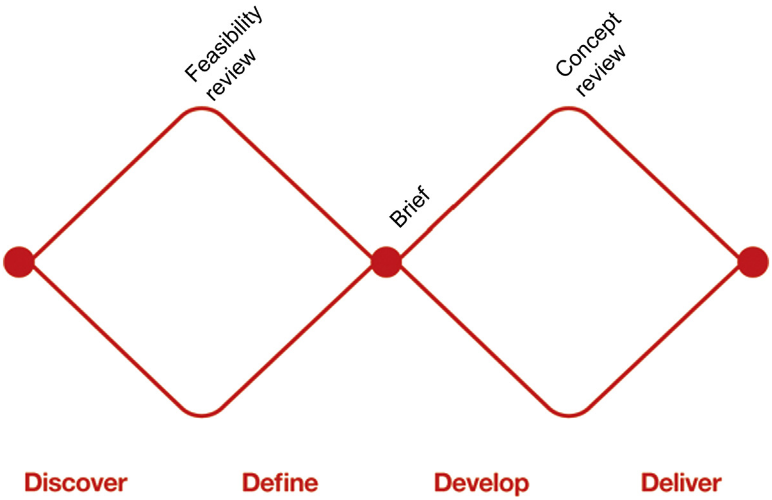


FIGURE 19.4
Double Diamond diagram (Design Council, 2005).

MATERIALS EXPLORATION VERSUS SELECTION

To explain the difference between materials exploration and materials selection, I make use of the double diamond diagram (Figure 19.4), developed through in-house research at the Design Council (2005), as a simple graphical way of describing the design process. In short, (1) Discover marks the start of the project. This begins with an initial idea or inspiration, often sourced from a discovery phase in which user needs are identified. (2) Define represents the definition stage, in which interpretation and alignment of these needs to business objectives are achieved. (3) Develop marks a period of development where design-led solutions are developed, iterated, and tested within the company. (4) Deliver represents the delivery stage, where the resulting product or service is finalized and launched in the relevant market.

In the traditional design process, materials selection is a process that takes place at the later "develop" stage where the materials selection criteria are defined by context of manufacturing and costs to realize an already mature product concept. The context in this phase is very concrete and decomposed, which makes it possible to select which materials or processes are appropriate and which are not in a very analytical way.

If we consider materials at the more abstract and holistic front end of the design process, the "discover" phase allows us to include aspects of business strategy and user needs. The new relationship of designers and materials that has a more research character finds its home in this early phase of design, also called the fuzzy front end of the design process. The difference with the former materials selection process at the develop phase is that this early phase is more holistic and abstract where materials can be used for goal forming (instead of product realization).

In Table 19.1, I summarized the different characteristics between the two phases.

Table 19.1 Different Characteristics between "Discover" and "Develop" Phases of a Design Process

Discover	Develop
Holistic and abstract criteria	Concrete and decomposed criteria
User needs and business strategy context	Cost definition and manufacturing context
Goal forming (defining)	Goal finding (making)
Need for inspiration (sketching)	Need for definition (e.g., CAD drawing)
Exploring materials	Selecting materials

To serve the different context of the discover phase in the design process, I started focusing on using a different method that supports the exploration of materials in the beginning of the design process. van Bezooyen (2002) documented this approach by originating the Material Explorer concept during his Masters degree research at the Delft University of Technology, and is something he now calls "materials driven design".

MATERIALS DRIVEN DESIGN

Materials driven design is all about bringing materials at the beginning of the design process. This can be by using materials samples to broaden the idea generation or by using a single material as starting point to explore possible applications.

Traditional design methodologies are often focused on sketching and visualizing. Materials driven design is all about hands-on explorations and prototyping with materials. The challenge is not to develop perfectly finished presentation items, such as renderings, but more raw/rough objects made of real materials within a workshop environment. The use of materials is not meant to realize a finished product but more as a driver of the creative "finding" process by evoking and concretizing ideas. In other words, materials driven design turns around the traditional design process. Instead of starting with solving a problem and defining materials requirements, materials driven design is all about starting with a given material, or set of materials, and discover its opportunities. Unlike problems, functions, or forms, materials themselves are the starting point of a project.

The fuzzy front end is critical to defining the nature of the problem that is being addressed through design (Rhea, 2003). The term fuzzy front end is increasingly being used to describe the early stages of the innovation process where ideas form. There is a level of ambiguity at this phase of the new product development process, and the process is largely unstructured.

In art education, it is very common to explore and experiment with materials to discover their qualities, and abuse them or create unexpected forms and functions. The title of this chapter is "Materials Driven Design" and not "Materials Driven Art". There are differences between designers and artists in the use of materials. Without generalizing, we can say that the use of materials in art is more dedicated to the artist's person and her/his need for expression. In other words, the material is a medium to express the artist's feelings. Within design, the role of materials is more functional and pragmatic. The choice of materials is more focused on the experience of the end user than on the expression of the designer's feelings. This difference between art and design is the reason why I consider materials driven design being something different from an artistic approach to materials selection. Also, artists have a more craft-based approach to materials and often know one or few materials very well. The designer's challenge is to know many materials a little and specialize where necessary. During their career, designers often develop (or should develop) a personal library that brings together their materials explorations documented as different types and combinations of materials and processes.

Exploring materials is one of the biggest challenges for designers. Today's enormous range of materials requires designers to follow a process of creative and analytical research to find the right material for the right product. Unlike a carpenter who is mainly using woods, designers are challenged to think in solutions made of woods, ceramics, metals, plastics, composites, and more material solutions that the market has to offer. In other words, designers need to understand and think in different materials and material combinations. Understanding materials is more a process of exploration that involves knowledge and skills developed through the hands-on experience of properties such as density, stiffness, glossiness, texture, coloring, processing qualities, and sometimes smell. Gathering these experiences is a way of "learning by doing". This so-called doing is a natural way of learning that is very common to newborn children starting to understand our physical world by touching and experiencing their environment. Materials driven design is all about this natural way of learning in developing more understanding of materials in design.

THREE CASE STUDIES

To demonstrate the effect of a materials driven design approach, I will review three case studies where materials have been the starting point for design, materials help designers to discover alternative solutions, and where materials support strategic thinking.

More creative (Public)

Materials Utopia (2010) is the title of a satellite exhibition developed for the International Design Festival Berlin (Figure 19.5). The exhibition and workshop were developed in collaboration with the Panatom Gallery, an art gallery in Berlin that exhibits at the intersection of art and design.

FIGURE 19.5
Materials Utopia exhibition (2010).

Challenge: Unlike exhibiting a finished product, we wanted people of all ages to work with materials and create something unique that could be exhibited within an art gallery. We liked the plasticity of materials but realized that processing plastics required (molding) tools with temperatures that might be dangerous to children. The use of different materials and tools might lead to a kind of recycling workshop, which was not appropriate in a gallery setting. Also, we trusted in earlier experiences that (material) limitations feed people's creativity.

Approach: We decided to focus on a material that is surprising, easy to shape, and with sustainable sourcing. During our research, we discovered a biodegradable chewing gum sourced from the rain forests of Mexico and decided this matched our needs. We created a laboratory setting with chewing gum and edible colorings and pigments, and invited people to create their own sculpture, an idea, a future, all made of organic chewing gum.

Outcomes: During 4 days, over 300 sculptures were made by hundreds of visitors from all ages and nationalities. The material provided a universal language and we were surprised by the joy of participation and creativity of the creators. During the workshop days, we learned that many people do not know that most mass-produced chewing gums use artificial, petrol-based polymers as substitutes for natural chicle. This allowed us to discuss sustainability issues and materials on a very enjoyable way with curious visitors.

More sustainable (Design)

Turning around the design process by finding new applications for one or few materials allows a more holistic approach that does not only consider the surface or finishing of an almost finished product but looks at the bigger picture of a product's life cycle.

Challenge: During the 'It's Not Easy Being Green' project by Raché and van Bezooyen (2012), one of the challenges was to support designers and companies in finding new or unconsidered applications for materials that have a potential for more sustainable products due to their lightness, durability, local sourcing, intelligence, or recycling potential for applications such as packaging, furniture, housing, or transportation (Figure 19.6).

Approach: Brainstorming sessions on the qualities of one or few materials. Sketching with materials to find new application ideas that improve or transform existing products, or are based on improving

FIGURE 19.6
It's Not Easy Being Green impressions (2011).

the life cycle of existing products from extraction, production, distribution, and consumption to disposal.

Outcomes: The combination of tangible opportunities (materials samples) and a holistic approach (life cycle thinking) often quickly results in innovative product ideas. The proposals should be discussed with the participating teams to review the life cycle and discover possible market opportunities.

More competitive (Business)

Materials play an important role in the perception of brands. For instance, since the 1950s, the Rimowa suitcases are known as "the luggage with the grooves". These iconic grooves have become a distinctive marking, a materiality that supports brand differentiation, Material & Identity (2007).

Challenge: Support (young) entrepreneurs with methods for more strategic use of materials in design and branding (Figure 19.7).

Approach: Demonstrate case studies of existing products and brands that are using their materiality as a strong part of their brand identity. Based upon diverse characters, teams of entrepreneurs are challenged to develop an object for sitting (not a chair) for different personalities. Collages are made to describe each personality whereafter material samples are provided to translate the (visual) identity into tangible qualities for the sitting object. Finally, the object for sitting is sketched in combination with positioning of material qualities.

Outcomes: Based on the different personalities, the different teams deliver very different objects for sitting. Teams without designers often do not question the form of the sitting object and use the materials samples to "stylize" a chair. Teams with more abstract thinking are able to let the form follow the selected materials.

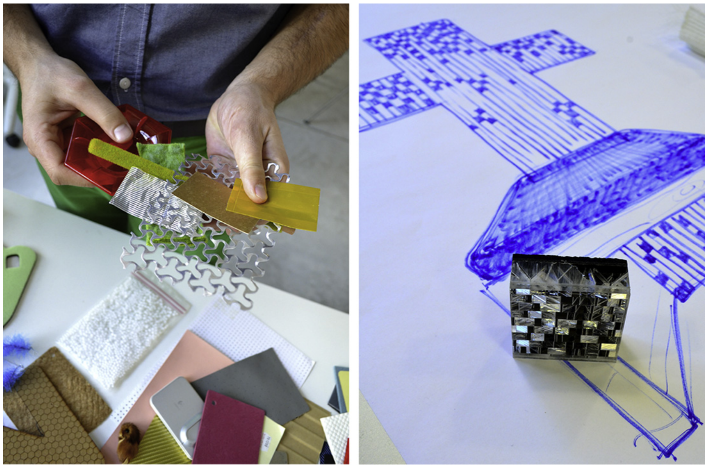


FIGURE 19.7
Design management workshop impressions (2012).

CONCLUSIONS

Materials driven design is not a scientific method and is still in an explorative stage but through workshops and exercises I am getting a better grip on the do’s and don’ts of bringing materials at the beginning of the design process. For instance, with too many materials samples, designers are easily overwhelmed with the opportunities of materials and easily loose concentration. During short (1 or 2 days) workshops, it is even better to focus on a single material to discover as many applications as possible. Further, prototyping, testing, and adapting three-dimensional objects or structures with basic materials is a powerful way for early user involvement in the process of new product development.

All together, materials are wonderful springboards for ideas. I experienced that by presenting materials at the beginning of the design process that designers are more focused on thinking about surfaces, structures, colors, and sensorial qualities in their idea generation. Instead of finding a material solution for preset forms and functions, exploring materials allows us to think in new ways and sometimes reconsider premature forms and shapes.

All together, the ultimate goal of materials driven design is to provide people the perspective of a more sustainable future by making them comfortable with change (by exploring material alternatives), by supporting human creativity (through limited resources), and by offering new solutions for old problems (with new and unconsidered materials and technologies). All together, materials driven design is about discovering. As the Hungarian biochemist Albert Szent-Györgyi (1893) describes it: “Discovery consists in seeing what everyone else has seen and thinking what no one else has thought”.

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CHAPTER 20

Interaction between Functional and Human-Centered Attributes in Materials Selection

Kevin Edwards
Aston University

CONTENTS

Most products are made from an assortment of different materials. The materials have to be processed into shapes to provide particular functions and characteristics. Correctly selecting the materials, among other things, is critical to the success of any product (Hodgson and Harper, 2004). However, except for the simplest component, the process of selecting materials is complicated (Brechet et al., 2001). This is because of the need to match a set of contradictory design requirements (functional and user centered) to a range of material properties and characteristics, respectively, that are different for each material. Add into the mix the use of new (or novel) materials and processes and advanced (or innovative) designs that exploit the boundaries of what is currently available and the whole process can become overwhelming. This can and often does lead to simplification and compromise in design and in choice of materials, resulting in mediocre products and poor satisfaction with regard to the user (Ljungberg and Edwards, 2003).

Materials Experience. http://dx.doi.org/10.1016/B978-0-08-099359-1.00020-5

There are methods available for helping select materials and these have proved most effective for product functional requirements, i.e., technical design. The methods are systematic and depend on matching the desired material property attributes against those from available materials. The most widely used materials selection method is based on performance indices and materials' property charts (Ashby, 2010). The method is also implemented as a computer software tool (CES, 2012). There is much less support available for nontechnical so-called personality (e.g., aesthetics and emotional attributes) requirements, i.e., industrial design, despite it being equally as important to the success of a product. This is mainly because the aspects associated with industrial design do not lend themselves so readily to formal systematic procedures and information on material characteristics is less available. An "online" materials knowledge base (Material Explorer, 2012) allows rudimentary searches by technical and sensorial qualities.

Product design ideally comprises both technical and industrial designs in a single unified process (Ulrich and Eppinger, 2004). Carrying out technical and industrial design as two separate activities is seen as problematic, leading to design solutions that might not fully exploit the qualities of materials. Also, because of the support available for helping to select materials, satisfying technical design requirements is relatively easier than satisfying industrial design requirements. However, the properties and characteristics of materials are interrelated and should not be considered in isolation. Therefore, simultaneous consideration of both technical and industrial design aspects when selecting materials is important but challenging.

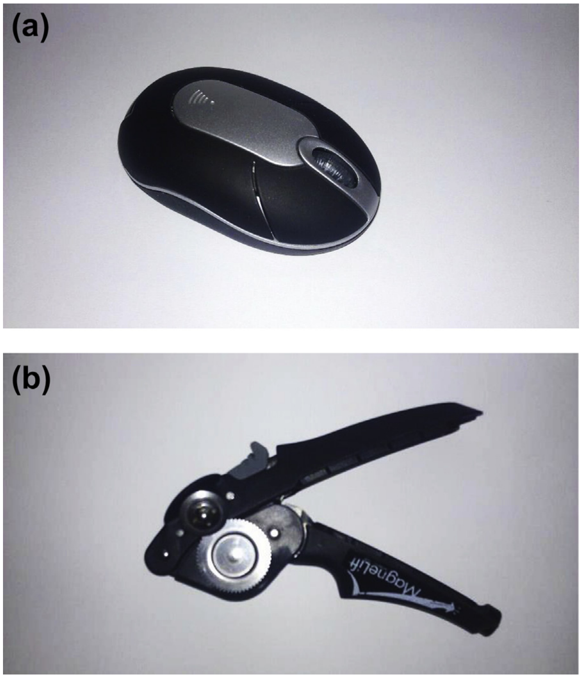

FIGURE 20.1
Example products that blend technical and industrial design: (a) computer mouse and (b) can opener.

Figure 20.1 shows a couple of typical products available on the market that successfully blend industrial and technical designs. Without explaining their functions, each handheld product is a complex assembly of components; the computer mouse (an electronic office product) comprises externally switches and internally electronics, while the can opener (a mechanical kitchen product) comprises levers, spindles, and wheels. The main working parts of the latter product are highly visible, while for the former product, are hidden from the user. Although arguably both the products are utilitarian, there is good attention given to aesthetics and ergonomics in terms of shape and materials utilization while satisfying different technical functions. The use of durable polymer materials dominates in these cost-sensitive mass-produced products, with shape, color, and surface texture created during the molding process, eliminating the need for further processing.

In the sections that follow, product design is investigated from the perspectives of both technical and industrial designs by analyzing the effect of the different approaches taken and priorities given on the choice of materials. The interrelationship between the properties and characteristics of materials is discussed and the resulting speculation and compromises made as a consequence of the complexity of contradictory information. Strategies are considered that support decision making by facilitating conflict resolution between opposing design requirements and material attributes in order to select a set of feasible materials.

THE MATERIALS SELECTION PROCESS

In general, identifying, evaluating, and selecting materials is an open-ended problem solving process with more than one solution (Deng and Edwards, 2007). As a consequence, selecting the optimum material(s) for a product design is not easy. Also, the choice of materials will vary depending on the stage of the design process, from a large range of possibilities at the concept stage when design information is imprecise and changeable, to a select few at the detailed stage when design information is more specific and stable. In effect, materials selection can be considered to be a process reflecting the design process itself. It begins with initial screening of all possible materials, through comparing and ranking of alternative materials, to selecting the optimum materials. At each stage, numerous quantitative methods are available to assist in evaluating materials (Farag, 2008). In the case of improving existing products as opposed to developing a new product, which is a more regular design activity that might also involve materials substitution, the materials selection process might start at an intermediate stage but it will still be necessary to understand the reasons for the use of existing materials.

Materials selection in technical design

The materials selection process already described is more closely associated with the activities of technical (or engineering) design. As a consequence, the approaches adopted for materials selection are by far the most developed for this design discipline. There are many systematic methods, most numerically based, with some implemented as computer software tools, for matching material properties with technical design requirements. There is also relatively easy access to a lot of detailed and verifiable technical information (materials and design) available from many different sources (organizations and publications). These facilities are particularly useful for novice product designers involved in materials selection.

Materials selection in industrial design

Products are differentiated not only by their technical functions but also by what the materials they are made of mean to the user (Karana, 2006). However, unlike technical design requirements, which are defined in quantitative terms that can be assessed objectively, industrial design characteristics are expressed in qualitative terms that are more subjective and difficult to interpret (Schifferstein and Hekkert, 2008). As a consequence, support for materials selection in industrial design is much less developed when compared to technical design. Further, the lack of structured approaches can lead to unpredictable outcomes and material characteristics not being given sufficient precedence in the design process. There is therefore a lot of reliance on the experience of the product designer when selecting materials.

Materials selection in product design

For effective materials selection in product design, both technical and industrial designs need to be thoroughly considered (Karana et al., 2008). Also, if the design of a product is to be successful, technical and industrial designs need to be carried out, ideally together. This means, however, that the divergent properties and characteristics of materials between themselves and each other need to be reconciled simultaneously. This is not easy because it is already difficult to separately match materials properties and characteristics with design requirements via technical and industrial designs, respectively. This often results in conflict when trying to satisfy design requirements with priorities having to be given to those requirements that are seen as essential and restricted by what materials will allow.

THE INFLUENCE OF DESIGN THINKING

The circumstances surrounding product design are further complicated by the fact that technical design and industrial design depend on different ways of thinking (Lawson, 2006). In technical design, deductive reasoning is employed, which when applied to materials selection depends on analysis, while in industrial design inductive reasoning is employed, which when applied to materials selection depends on synthesis (Ashby and Johnson, 2009). This means that there is a dichotomy with one problem solving processes being fully or partially opposed to the other and with the associated methods of materials selection potentially producing different outcomes. There are of course situations in product design where one approach is clearly better than the other and these tend to lie at the extremes of either technical or industrial design. Typically, product design requires a judicious use of both approaches to problem solving. Therefore, what is needed is a flexible attitude to materials selection, deploying both deductive and inductive reasoning in a balanced manner.

Applying selection methods

In materials selection, a set of design requirements is converted into a list of possible materials as shown in Figure 20.2(a). The process relies on access to databases (organized and ad hoc information) of different materials and products. The latter refers to existing product features, or use of materials in products, which are notoriously difficult to categorize for retrieval purposes and therefore mostly rely on experience when comparing with new designs. There are similar problems with material attributes, with characteristics as opposed to properties being more difficult to quantify, hence relatively more challenging to sort, locate, and use.

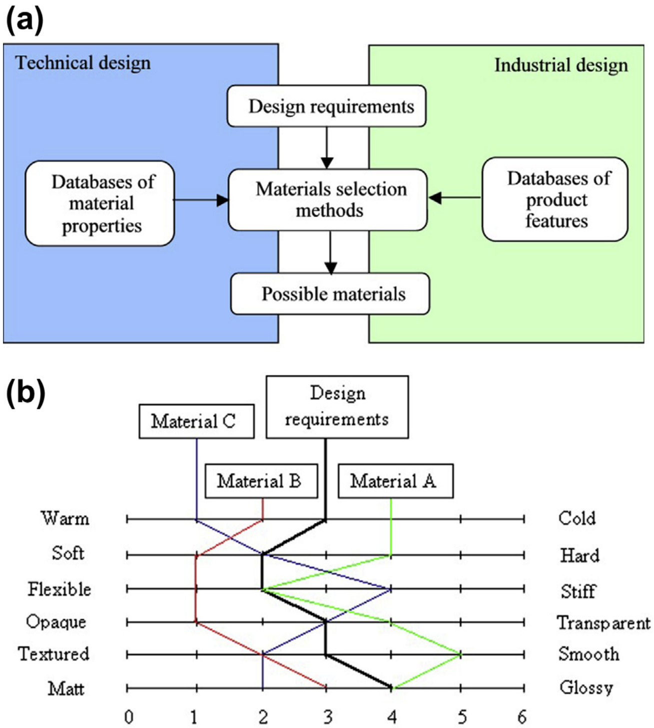

FIGURE 20.2
(a) The role of materials selection in product design; (b) comparing material characteristics against design requirements.

In technical design, the methods of materials selection are based predominantly on systematic analysis. The deductive reasoning behind the method relies on precise information, models, and sets of rules that can be manipulated to accurately match technical design requirements with material properties. In industrial design, the methods of materials selection are based predominantly on analogy and synthesis. The inductive reasoning behind the method relies heavily on past experience and the ability to match desired features with those of previous design solutions.

For a product to be successful, however, the methods of materials selection have to be combined strategically and used in such a way that it allows decisions to be made that are sensitive to the nature of the selection problem as the design evolves. If the information is quantifiable, then analysis can be used and if the information is qualitative, then synthesis can be used. Alternating between analysis and synthesis is therefore the usual consequence and the process needs to be carefully managed to avoid disagreement and inconsistency in decision making.

Supporting decision making

Selecting materials to satisfy technical and industrial design aspects via an integrated approach is difficult. However, with careful treatment, the decision-making process can be managed as the design evolves, gradually converging on suitable materials. The implications are that a more structured approach, however, will stifle innovation but this need not be the case. The most important point is that the approach is applied flexibly, allowing freedom for creativity as well as discipline. It is quite normal for material attributes to conflict with each other, possibly compromising the desired design requirements. A critical consideration of all relevant material properties and features will ensure not only their contribution but also an investigation of their interaction with each other (van Kesteren, 2008a). The resulting conceptual framework described, which is an integral part of the design process, allows a mixture of different selection methods to be applied strategically. This facilitates improved decision making but relies on ready access to design and materials information. It also allows for materials substitution in existing designs and new materials to be included in the decision-making process.

Materials information requirements

Any materials selection method will rely on suitable materials information (properties and characteristics) being available to support decision making. The materials information requirements depend on the method of selecting, the extent of product design issues, and the roles materials have to play within the product, i.e., functionality and personality (van Kesteren, 2008b). The level of detail required will also increase as the design progresses from the initial concept stage to the final detail stage.

Product designers can obtain information on materials from a variety of different sources:

- Application-related information is obtained from personal/company experience, materials/product testing, and materials used in similar products.
- Supplier provided information is obtained from direct contact, Internet, data sheets, brochures, material samples, and exhibitions.
- Openly available information is obtained from databases, journal/conference papers, and textbooks.

Unfortunately, not all information is available in numerical form, which makes it more difficult to specify, select, and compare different materials. The use of materials information also depends on the level of experience of the product designer. Openly available information tends to get used more in the early stages of the design process. Samples are useful for acoustic, tactile, and visual characteristics (Lesko, 2008). There is considerably more information available for material properties than for material characteristics; therefore, technical design is more supported than industrial design.

MANIPULATING MATERIAL ATTRIBUTES TO SATISFY DESIGN REQUIREMENTS

The nature of properties and characteristics of materials as already explained are quite different and therefore demand different methods of selection. Although some variation is common, the main categories of material properties and characteristics, each comprising a set of undisclosed attributes, are shown in Table 20.1. The technical properties of materials can be quantified and are therefore essentially easier to select than human-centered characteristics, which are more difficult to quantify. As a result, the availability of systematic methods and technical information means materials selection features more strongly in technical design than in industrial design. However, the material characteristics normally associated with industrial design are as important, including the evoking of human

Table 20.1 Main Material Property and Characteristic Categories

Technical Design: Material Property Categories	Industrial Design: Material Characteristic Categories
Atomic	Aesthetic
Chemical	Association
Environmental	Emotion
Mechanical	Ergonomic
Physical	Meaning
Processing	Perception

perceptions, emotions, associations, and meanings. It should be noted that all the categories in Table 20.1 have economic implications.

Materials selection methods and information for technical design are more highly developed than for industrial design. This is underpinned by the formal education and training associated with science and engineering disciplines. There is therefore an advantage in assimilating systematic methods and formatting of information from technical design and using them in industrial design. The generation of numerical data for characteristic attributes and adapting materials selection methods from technical design does help at least with higher level material searches. This allows consideration of material properties and characteristics on a more equable basis. However, skill is still required to carefully allocate numerical values to characteristics because of the subjectivity of perceived levels of sensory perception. This is because the characteristics are ephemeral and affected by different emotions, opinions, and interpretations.

It is possible to assign qualitative design objectives, efficacy scores estimated on a points rating scale (Cross, 2008). A feasible approach therefore for material characteristic selection is to use a "semantic differential scale" in which a seven-point one-dimensional scale is set between two opposite adjectives representing the extremes of an attribute. The material attribute is then assigned to a specific point on the scale; e.g., for the warmth attribute, a scale could range from warm at one extreme to cold at the other extreme. A set of similar scales is envisaged for all of the material characteristics. The resulting profiles for each material across the different scales can then be compared with each other and the relevant design requirements as shown in Figure 20.2(b). As well as comparing material characteristics, this approach also allows material characteristics and properties to be compared together, i.e., qualitative meaning and quantitative values, respectively. The scores could be added up for each material to choose the "best" material but the main benefit of using this approach is for making direct comparisons between different materials.

When selecting materials, it is normal for any material under consideration to fall into one of the following three categories as in Figure 20.2(b):

- Material A that meets or exceeds all the relevant design requirements.
- Material B that does not meet any of the relevant design requirements.
- Material C that meets some of the relevant design requirements.

The first category appears to be the most obvious choice. The second category appears to be the least obvious choice. The third category is not an obvious choice at first sight but depends on the circumstances. Therefore, the overall outcome is not straightforward. However, this simple categorization ignores the varying extent of each material characteristic meeting (or not meeting) the relevant design requirements. This is important because significantly exceeding the design requirements is inefficient and borderline under exceeding the design requirements might be acceptable in practical design situations. Also, in the case of material characteristics, some design requirements could be imprecise and/or interpreted intuitively.

The system of assigning numerical scores to material characteristics used in industrial design provides a means for directly comparing different materials that is analogous to that used for material properties in technical design. As a result, the relative effect of over (and under) exceeding of relevant design requirements for each material can be evaluated and ranked. The quantifying of material characteristics also helps to specify these design requirements more precisely. However, unlike material properties, which are based on verifiable numerical data and facts, material characteristics have to be assigned numerical scores subjectively.

Interaction effects in materials

A lot of the material characteristics and properties are related to each other, e.g., the soft/hard characteristic is related to both modulus and hardness material properties. The material characteristics and properties are therefore considered to be pseudo "coupled", i.e., not physically related but still affecting each other. This means that selecting material characteristics and properties in isolation might lead to contradictory decision making. It is important to avoid optimizing the selection of materials for satisfying technical performance and then subsequently undermine this when selecting materials for human-centered characteristics and vice versa. In practice, what tends to frequently happen is that products get designed predominantly from either a technical or an industrial design perspective. The leading perspective tends to then form the basis for the following perspective. At this point, the interaction between the material properties and characteristics become a potential issue and the experience of the product designer becomes essential to reconcile conflicting outcomes. The sequential approach, however, tends to lead to suboptimal use of materials because of the constraints imposed by previous decisions. This becomes even more problematic when a material characteristic interacts with more than one material property. The interrelationship between two material properties (A and B) and a material characteristic is illustrated in Figure 20.3(a).

The ideal circumstances are realized when materials selection is based on characteristics and properties occurring together but this is complicated. This means adopting a design process that encourages industrial and technical design being conducted simultaneously as shown in Figure 20.2(a). The problem is exacerbated because of the different vocabularies employed by industrial designers and engineering designers, often using similar terms with different meaning. The conversion of characteristics to numerical scores does at least allow material characteristics and properties to be more easily assessed at the same time. The most significant benefit is realized when selecting materials in the early stages of the design process. This is because a large number of materials need to be compared that are based on approximate materials information only to see if they meet the relevant design requirements. This reduces the effect of subjectivity on allocating numerical scores to material characteristics, allowing

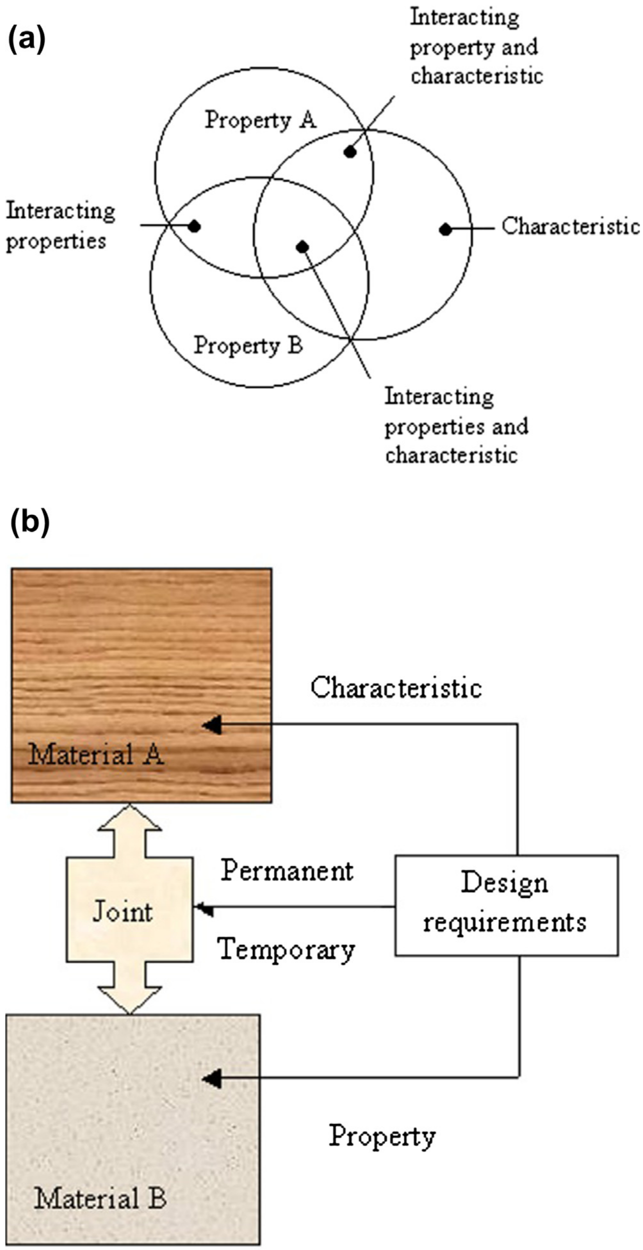

FIGURE 20.3
(a) Interaction of material properties and characteristic; (b) achieving design requirements from different materials.

material properties and characteristics to be compared together using materials selection methods in technical design.

Materials used in combination

If the design requirements cannot be easily satisfied by the properties and characteristics of a single material, then two (or more) materials can be and normally are considered. There are available multiphase or composite materials and recently functionally graded materials that for design purposes can be treated as special single materials. These materials are mostly used to provide enhanced properties over conventional materials by virtue of the integration of their different constituents but often possess distinctive directional properties. In the more general case under consideration, the materials are considered to be discrete only. Typical examples are coatings applied to substrate materials to provide superior surface properties, e.g., corrosion or wear resistance, or material inserts/attachments to provide localized specific characteristics that cannot or do not need to be provided by substrate or base materials, e.g., screwdriver with metal shaft and comolded polymer handle. In both these examples, there is a primary and a secondary material involved (with properties and characteristics) but each material is reliant on the other for the proper functioning of the overall product.

There are consequently two different approaches, both widely used that can be considered for satisfying the design requirements as follows:

- Using a single material to satisfy both the characteristic and property requirements (as explained previously).
- Using two different materials, i.e., one material (A) to satisfy the characteristic requirement and another material (B) to satisfy the property requirement as shown in Figure 20.3(b).

The separating of functional and user-centered design requirements across different materials reduces any problems of property/characteristic interaction and allows more flexibility in the choice of materials (Edwards and Deng, 2007). However, there is now the added complication of deciding how to adequately join the different materials together to satisfy the interface requirements (permanent or temporary). The substrate materials influence the choice of the most effective available joining method, e.g., fasteners, welding, or adhesives. When the secondary material is used to impart a characteristic to a primary functional material, i.e., load transfer between the substrates is not a major issue, then this is less demanding. The joint itself in most cases is another material, e.g., adhesive, weld zone, bolt/screw/rivet, etc., and in certain circumstances will provide material characteristics that can be exploited in industrial design (e.g., aesthetics).

Materials substitution

As well as new product development, a large amount of product design involves improving existing products, e.g., cost reduction, technical advantage, meet new legislation, restyling, etc. This often means simply substituting a new material to replace an existing material. However, this might not achieve optimal use of the new material. Therefore, to be completely effective, the whole or part of the product design might need to be revisited in order to fully exploit the properties and/or characteristics of the new material (Edwards, 2004). It may in fact also be necessary to replace adjoining materials to be able to introduce the new material. The existing design, together with the list of new design requirements, then forms the basis of decision making.

Extra care needs to be taken when selecting a material for substitution because the different properties of the new material might not be compatible with existing adjoining materials, potentially leading to premature failure of the product, e.g., a polymeric material replacing a metallic material to save weight might lead to adverse stress concentrations because of the differences in stiffness. However, if the material replaced has essentially the same properties or is the same material locally modified, e.g., receiving a surface treatment to change the characteristic, this might not be such a serious problem. In practice, substituted materials will not be fully compatible with the materials being replaced but it is important to fully understand the differences so that any adverse effects can be recognized. In this case, the materials selection considerations for materials used in combination described in the previous section are recommended.

Total product implications

Apart from the simplest single material component, products typically comprise an assembly of different components and materials. The assembly will be designed in such a way as to provide a product that performs the necessary overall function and satisfy user-centered needs. Selecting materials to satisfy the whole of a product is complicated and therefore tends to be addressed in detail at the component level for technical design and more holistically at the product level for industrial design (Baxter, 1995). The components are either fixed (analogous to joining materials in the section 'Materials used in combination') or free to move relative to each other, e.g., bearing or hinge. In both cases, it is important to consider the main part of the components as well as the interfaces when selecting materials for satisfying functional and/or user-centered needs, also deciding if another (interface) material is necessary.

To facilitate assembly, a lot of products comprise a main component, or structure, onto which other components are attached, e.g., the chassis of a motorcar. This structural component may also form the outside of the product and in this case the aesthetics could also be important. The larger the number of components attached to the structure the more difficult it is to satisfy the design requirements. Selecting a suitable material for the structure is very demanding, which for economical and processing reasons tends to be a single material throughout. This often leads to compromises being made to satisfy all the design requirements, i.e., some areas of the structure might have to be "overengineered". Composites allow the properties of the material to be tailored over the structure to more closely match the design requirements. However, it is difficult to change the overall function of the product. Alternatively, some products are designed as a set of modules. This allows the product to be upgraded or its function changed more easily by replacing existing modules. A lot of manufacturers exploit these approaches by producing a range of different specification products derived from a common "base" product, e.g., different shaped exterior panels to affect styling and different components to affect performance of a motorcar.

CONCLUSIONS

Materials selection forms a key part of the new product design process. However, for products to be successful, materials must be selected not only to achieve technical performance but also to satisfy user-centered needs. This necessitates fully taking into consideration the diverse requirements of both technical and industrial designs, which is challenging. Ideally, these viewpoints need to be addressed at the same time and not in isolation to ensure that all relevant material attributes are considered and to reduce the need for having to make assumptions based on incomplete and approximate information. The difficulty is compounded by the fact that several systematic materials selection methods and computer-based tools, and numerous databases of material properties, exist for technical design but unfortunately not for industrial design. This is largely because of the ad hoc nature of industrial design information and dependence on intuition and experience making it difficult to classify and choose material information. There is scope in industrial design for adopting the materials selection methods used in technical design by quantifying material characteristics. Although still based largely on a degree of subjectivity, the numerical approach is particularly useful in the early stages of the design process when a lot of materials using approximate information have to be considered.

Despite the reducing number of materials under consideration, the later stages of the design process are difficult to undertake for materials selection because the information becomes more precise and detailed. This makes it even more demanding to adapt or combine the current methods of materials selection serving technical design for use in industrial design. To supplement existing methods of materials selection, multicriteria decision making (MCDM), with its routes in operations research, has recently begun being applied to materials selection (Jahan et al., 2010). MCDM methods support enhanced decision making in materials selection, allowing simultaneous consideration of design requirements, material attributes, and component configurations. There is the potential for incorporating material properties and characteristics and different material interactions, which is the subject of current research.

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CHAPTER 21

Modeling Materials Technology and the Designers' Perceptual Span

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CONTENTS

The model of designing shown in Figure 21.1 demonstrates that in the 1970s (at least at the Design Education Unit at the Royal College of Art (RCA)), the role of modeling in designing was well understood. There needed to be interaction between the "mind's eye" and external models through all the senses in order to facilitate designing, "thinking through doing" or "thinking through action". As Baynes (2009:54) noted, the diagram needed further development "to distinguish more clearly between the *mental* models used in imaging and the *externalized* models used to represent cognition in physical or symbolic forms", but it presented a secure foundation on which design research could build.

It is equally well understood that modeling increases the perceptual span of designers (Jones, 1970). As modeling tools develop, the complexity of the tasks that a designer could address and the sophistication that the designer might achieve are enhanced, but this is not, of course, a causal relationship. In a recent analysis of the effectiveness of contributions to design education research, I suggested that the following three categories provided a useful strategy for considering such relationships:

- *The designer(s): the individual(s), their capabilities, and their competences for designing*
- *The design context: the analysis of the knowledge, skills, and values that they might possess*
- *The interface: tools for designing and organizational structures that enhance designers' capabilities, competences, and access to their context* (Norman, 2011).

Materials Experience. http://dx.doi.org/10.1016/B978-0-08-099359-1.00021-7

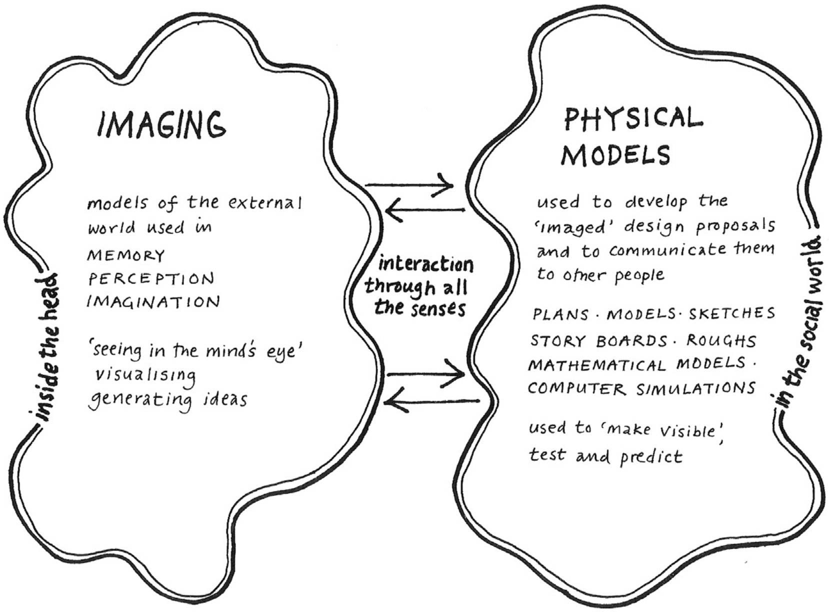


FIGURE 21.1
Diagram from the 1970s identifying the relationship between imaging and physical models. © *Ken Baynes (2009:54).*

This chapter builds from the analysis of "tools for designing" as supporting the interface between the designer and the design context. The relationships governing this interface are complex. This contribution explores how some models of materials technology that have been brought forward have sought to increase aspects of the designer's perceptual span. It is inevitably "preliminary" in nature, because this is an under-researched area of human activity, and one in which this book can provide a useful step forward.

The following questions are addressed, albeit selectively:

- What kinds of mathematical models have been developed? What do they enable designers to do?
- What kind of visual models have been developed? What do they enable designers to do?
- What is the nature of technology for the purposes of those engaged in designing? (Or "technology for design" (Norman, 1998)).

For this chapter, in particular:

- What is the nature of materials technology for design?

The development of "materials libraries" and their popularity with designers has demonstrated that designers have not been content with the mathematical and visual models that have been made available to them. Direct physical interaction with materials seems to bring matters to the attention of designers within their decision making that models of those materials do not, and it is important to explore why this turns out to be so.

MATHEMATICAL MODELS OF MATERIALS TECHNOLOGY

Mathematical models of materials are at their most straightforward to interpret when they represent a well-defined technology and are applied to well-defined problems. Consider the concept of tensile strength, which is often given the symbol "σ". The tensile strength of a group of materials such as aluminum alloys can be stated as "58—550 MPa" (Ashby, 2009:268) depending on the particular alloy selected. Other less well-defined properties, such as the corrosion resistance or weldability of aluminum alloys, might determine the particular alloy selected, but once determined its tensile strength will be known within a narrower range. This is not yet sufficient information on which to base a design decision because materials fail in tension in a variety of ways: for example, metals, polymers, and ceramics result in different shaped stress—strain curves (see Ashby, 2004:23—24). To make judgments, it will be necessary to understand concepts such as the 0.2% yield strength (metals), the onset of nonlinearity (polymers), and fracture strength (ceramics). And so, although each material tends to behave slightly differently, there is hope of the knowledge required being sufficiently bounded in order to be "knowable".

The context of the task can provide further confidence. For example, standards will define test procedures through which materials are to be evaluated. As the results obtained will depend on the size of the sample and the rate of loading, this is important. Similarly, it is crucial to know the design stresses that are appropriate for different applications. Analysis of a problem situation from first principles can take the designer a long way along the road, but, in the light of experience and the unexpected, design standards will state required design stresses for the designer to apply. So, for the "engineering designer" tackling a well-defined problem, there is good reason to believe that the tools provided by mathematical modeling can result in a robust solution, although it is not straightforward. In relation to the discussion of "materials technology for design", it should be noted that even when addressing what an engineering designer might regard as a well-defined problem and using an "engineering material", specific knowledge of the behavior of that material and some of its less-definable characteristics are important.

With the advent of information technology, the possibility of extending the power of such models of materials by developing tools for designing supported by databases became apparent. Cambridge Engineering Selector (CES) software is perhaps the most well known. Information is provided concerning materials and processes, some of which are numeric and some of which are nonnumeric. This is of course extremely helpful, but, as with all models of reality, there are limitations and inherent risks associated with misinterpretation.

The outcome of interacting with this design modeling tool is dependent not only on the quality of the information and optimization procedures available, but also on the individual capability of the designer. From a computer programming perspective, it is useful for the nonnumeric information to be in binary format (i.e., recycle "yes/no", or downcycle "yes/no"). However, sometimes what it represents is not so straightforward as this representation might suggest. For example, recycling polymers is critically dependent on color control. If colors are mixed in even small amounts "browns and grays" are the outcome. The technical "solution" at that point is to downcycle and swamp the color pigments in the recycled polymer, for example, with carbon or chalk, in order to make black or white, lower grade products. But it is in these marginal areas that "creativity" can be employed. What if you control the colors by avoiding fully melting the polymers and combining them under heat and pressure?

In 1996, Craftspace Touring curated the Recycling exhibition and one of the artifacts included was the Recycled Consumer Plastic (RCP) chair by Jane Atfield. In the exhibition catalog, she commented as follows:

> While at the RCA I reused leftover materials from factory processes such as industrial recycled felt for armchairs. I also incorporated found objects into my work and began importing recycled plastic from America. This led to a two year project researching and developing a similar post-consumer recycled plastic material, made from high density polythene from empty shampoo, milk or detergent bottles such as Domestos or Frisk. Which I now sell through the company Made of Waste [… now Remarkable Smile, see http://www.remarkablesmile.co.uk]. My motivation with this material has been to respond to the environmental issues and to extend the use of discarded objects into a new and evocative material.
>
> **(Craftspace Touring, 1996:8)**

This is anticipating the emerging concept of "upcycling", which is discussed elsewhere in this book. Materials supplied by Remarkable Smile have been used to create products such as interior and garden furniture, shop counters, signage, kitchen work surfaces, and sinks. However, the key point here is that the development of the material was not based on "knowing that" polythene could be recycled, but developing the "know-how" to recycle it in a particular way that was valued within the designer's cultural context.

Design tools such as the CES database can help the designer, but only up to a point. They embody the hidden danger of presenting what is normal, whereas designers are frequently testing the boundaries of what is possible. For example, process selection databases often put a lower limit on the market size for which they are viable, say >10,000 for injection molding. However, this situation, like many others, is actually more "gray" than "black and white" and creativity in mold tool and component design, together with appropriate material selection, can challenge such limits. The CES database can bring appropriate materials and processes to the designer's attention, and, if they are operating beyond their personal knowledge and experience, this is invaluable. However, personal expertise and its creative application can challenge what is "normal".

Table 21.1 shows technical data for a collection of materials all of which have been used to create successful acoustic guitar soundboards (Pedgley et al., 2009). It has also been demonstrated that listeners are unable to distinguish polymer soundboards (made from structural polycarbonate foams, Forex EPC, and Palsun Foam) from wooden soundboards in high-quality, luthier-made guitars (Pedgley and Norman, 2012). Where would be the clues in the information contained in typical existent uses of foamed polycarbonate or material data sheets that this might be a possibility? Conventional wisdom would suggest searching for a material with a value for E/ρ (stiffness to weight) similar to wood, but the data in Table 21.1 would suggest there is little point. Carbon fiber-reinforced polymer (which is an effective soundboard material on Rainsong guitars, see http://rainsong.com/) has an E/ρ value over 3 times that of Sitka spruce, which in turn has an E/ρ value over 14 times greater than structural polycarbonate foams as used by Cool Acoustics (see http://www.coolacoustics.com/): a range of over 40:1. The clue to use structural polycarbonate foams actually came from Rob Armstrong's

Table 21.1 Properties of Guitar Soundboard Materials, Originally Compiled in Pedgley et al. (2009):169

Property	Sitka Spruce	White Cedar	Forex® EPC	Palsun® Foam	Aluminum Alloy	CFRP
Young's Modulus E (MPa)	11,000	6400	1200	1500	69,000	150,000
Density ρ (kg/m^3)	400	320	650	800	2700	1700
E/ρ	27.50	20.00	1.85	1.88	25.56	88.24
E (% relative to Sitka spruce)	1.00	0.58	0.11	0.14	6.27	13.64
ρ (% relative to Sitka spruce)	1.00	0.80	1.63	2.00	6.75	4.25
E/ρ (% relative to Sitka spruce)	1.00	0.73	0.07	0.07	0.93	3.21
Fiber reinforcement	Cellulose + lignin	Cellulose + lignin	None	None	None	Carbon + epoxy
Directionality	Wood grain	Wood grain	None (isotropic)	None (isotropic)	None (isotropic)	Carbon weave

CFRP, carbon fiber-reinforced polymer.

personal expertise, an internationally recognized luthier who has made over 800 guitars (see Pedgley et al., 2009, for a more detailed discussion).

The primary difficulty in the case of the guitar soundboard is that the problem is ill-defined. There is no "perfect voiceprint" for an ideal guitar. Similarly, the problem that Jane Atfield faced was ill-defined. There is no "perfect image" for an ideal recycled polymer sheet. These are multidimensional "wicked problems" (Rittel and Webber, 1974) of the kind that designers are expected to resolve on a regular basis. Their resolution depends on developing "know-how" as well as "know-that" (Ryle, 1949). The resolution of such complex problems depends on the designer having developed sophisticated pattern recognition capabilities. The human brain of an expert designer is capable of seeing the way forward in the "mind's eye". Such experiential knowledge is hard won.

Without such expertise, there is a strong human tendency to resort to heuristics in the face of complexity. "Satisficing" is the term originating from Herbert Simon's (1957) Nobel Prize-winning work that described individual judgments as being made within a bounded-rationality framework. It refers to problem resolutions that are acceptable or sufficient positions. In 1974, Tversky and Kahneman published research building on Simon's work and described some of the systematic biases that affect management decisions. As Bazerman reported:

> Their work, and work that followed, led to our modern understanding of judgement. Specifically, researchers have found that people rely on a number of simplifying strategies, or rules of thumb, in making decisions. These simplifying strategies are called heuristics. As the standard rules that implicitly direct our judgement, heuristics serve as a mechanism for coping with the complex environment surrounding our decisions.
>
> **(2002:5)**

He goes on to describe in detail three general cognitive heuristics that "affect virtually all individuals" (2002:5):

- the "availability" heuristic, a bias toward the familiar;
- the "representativeness" heuristic, a bias toward known categories;
- "anchoring and adjustment", a bias toward an initial starting position.

In the context of a discussion of materials technology for design, these heuristics are significant. All of them could be seen as influencing the choice based on "conventional wisdom" of wood for soundboards: it is familiar, is from a known category, and provides a safe starting position. Starting with "Sitka spruce" and moving to mahogany or bamboo are moves that lie within people's comfort zone. Choosing structural polycarbonate foams is perceived as radical because it is unfamiliar, from a different category, and far removed from a conventional starting position. None of this is rational. It is not as if the first makers of soundboards considered all the options and rejected polymers in favor of wood. Wood was the option.

It turns out that you can make polymer guitars having sound characteristics lying within the range commonly associated with wooden guitars, but it must come as a surprise to no one that there is no market. Although luthiers and materials scientists would probably have no difficulty with the concept, people in general will. The development of the polymer acoustic guitar was a research project designed to challenge boundaries, and in the end ran into difficulties during commercialization. Designers can choose to challenge boundaries, but, if sustained production and distribution is the goal, then material choices must reflect those objectives. What does this say about appropriate materials technology for design? Essentially, material selection is as much about understanding people and the market as it is about the product requirements. Much of it is moderated by people's values and judgments about the "right" materials for things—a complex mix of factors where rationality is not always dominant.

Heuristics are one strategy for avoiding the complexity associated with design decision making in multidimensional contexts, but not the only one. Sustainability is emerging as a highly complex agenda that impacts on materials technology. How can the most sustainable material be chosen? Other chapters in this book discuss this matter in detail, and consequently "ecoindicators" are only briefly mentioned here, as an example of an alternative mathematical modeling strategy developed for resolving complex design situations. Life cycle analysis is complicated and time consuming. Consequently for designers who may not be experts on particular materials and processes and their impacts, ecoindicators have been developed. These aggregate the impacts of a material on humans, resource depletion, and biodiversity during its production into a single number. Rigid polymer foams have an ecoindicator of 400–440 millipoints/kg. Softwood has an ecoindicator of 6.3–6.9 millipoints/kg (Ashby, 2009). These numbers depend on judgments made about the relative importance of humans (current), resource depletion (future humans), and biodiversity (nonhumans) with which you might or might not agree. The ecoindicator saves the designer both from having to find out in detail about the materials they are using and considering the consequences. These tasks are effectively delegated. For guitar soundboards, the complicating factor is that it is normally thought to be necessary for the wood required to be close-grained and therefore slow growing, so it is not a "sustainable resource", at least in terms of current and near-future generations. Would it not be better to use recyclable polycarbonate for beginners' instruments and leave the high-quality tonewoods that remain available for highly skilled luthiers to use in their work? This might be a rational question to ask, but it is not really appropriate within a market-driven global economy within which such a policy would be next to impossible to regulate or enforce.

Unsurprisingly, an aggregated measure like the ecoindicator has been the subject of criticism. As Ashby puts it

> The use of a single-valued indicator is criticized by some. The grounds for criticism are that there is no agreement on normalisation or weighting factors, that the method is opaque since the indicator value has no simple physical significance, and that defending design decisions based on a measurable quantity such as **energy consumption** or **CO_2 release to atmosphere** carry more conviction than doing so with an indicator.
>
> **(2009:48)**

Measurable quantities also simplify complex situations, and there's many an inappropriate target been set based on what is measurable. If only everyone was an expert on everything!

VISUAL MODELS OF MATERIALS TECHNOLOGY

In order to focus the discussion of what visual models of materials technology might offer, a design task was given to sixth-form (17- to 18-year-old) students at a study weekend. The students studied

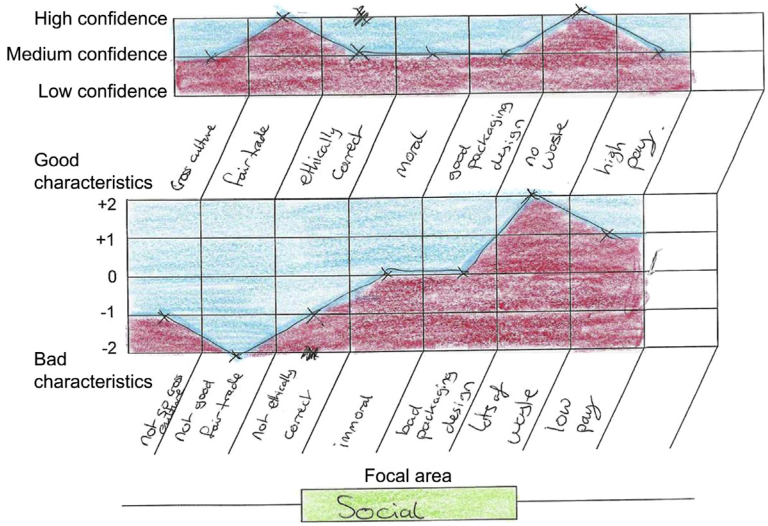


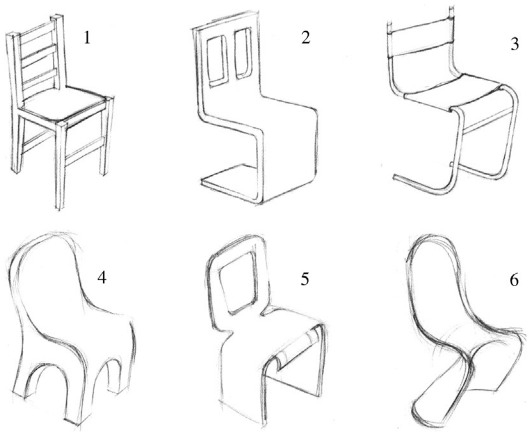
FIGURE 21.2

The "design abacus": a modeling tool for facilitating judgments in sustainable design. © Norman, (2006:28).

citrus juicers produced from a variety of different materials, illustrating the difficulty of making a design decision (Norman, 2006). Ecoindicators, or another measurable quantity, provide one strategy, but consider the visual tool developed for the Sustainable Design Awards (Capewell and Norman, 2003) by adapting the Integrated Design abacus provided by Shot in the Dark shown in Figure 21.2.

This modeling tool is not simplifying the task but supporting designers in engaging with complexity. Figure 21.2 shows the responses of one of the groups of 17- to 18-year-old students to thinking about the social issues surrounding this design decision. The students also considered environmental and social concerns as separate focal areas. Figure 21.2 shows the criteria that they felt to be important and, at the top, their assessment of their confidence in the basis of their judgments. It is a modeling tool for focusing attention and prioritizing "finding out" (research). Visual modeling tools have the capacity to scaffold the thinking of designers, and in dealing with greater complexity, such scaffolding is key. Visual models are capable of incorporating ambiguity in a way that is more problematic in mathematical models.

Of course, the visual communication of technology is not new and designers have been embodying technological information in visual form since mediaeval times (see Ferguson, 1977, for an authoritative account). Materials technology has also been commonly communicated through diagrams or animations. There are too many examples to provide a representative sample, but considering the example shown in Figure 21.3 serves to demonstrate some of their possibilities. The ambiguity of the sketches allows the designer to place the concept on which they are reflecting in their minds' eye into one of the categories, or perhaps to test it in several in order to explore the best fit. The material/process matrix provides detailed information concerning relationships that can be pursued further as necessary.



	Machining	Sheet forming	Drawing	Rotation moulding	Lay-up methods	Thermoforming
Solid wood	1					
Plywood					5	
ABS				4		6
Stainless steel	2	2	3			

FIGURE 21.3
An example of the visual communication of materials technology. *Ashby and Johnson, 2002:107.*

This kind of approach is both scaffolding the cognitive modeling process and providing avenues for further exploration. It is supporting designing both strategically and tactically and at a level of detail appropriate to the generation of early concepts.

As the complexity of the research agendas that materials technology for design embodies increases, for example, to include both sensorial as well as technical properties, it is inevitable that the visual communication of materials technology will both require and attract further research. The visual communication of technology was the subject of a recent PhD completed by Cheng-Siew Beh at Loughborough Design School (2012). As a graphic designer, she developed appropriate principles to guide the design of such visual images and applied them to some of the emerging models related to sensorial properties. Figure 21.4(b) shows an example in which the research by Elvin Karana (Figure 21.4(a), 2010) on the factors that influence the meaning people associate with a material is re-presented. When evaluated with masters and undergraduate students ($n = 47$), 70% preferred the redesigned graphic with the majority 67% understanding its key messages (Beh, 2012). In developing understanding of these influences, the designer can become better informed of the values of the user. The visual model illustrates that the same characteristics of the rapid communication of ideas concerning the scaffolding of cognitive modeling and guidance for future action are evident.

TECHNOLOGY FOR DESIGN

The discussion so far is sufficient to illustrate that the consideration of what constitutes technology for the purposes of those engaged in designing (technology for design to be brief) is problematic. In a paper published in 1998, the author developed the position first put forward in 1982 by a Working Party for the UK's Assessment of Performance Unit led by George Hicks. This argued that technology for design had to be considered as embracing three elements: knowledge, skills, and values. Knowledge

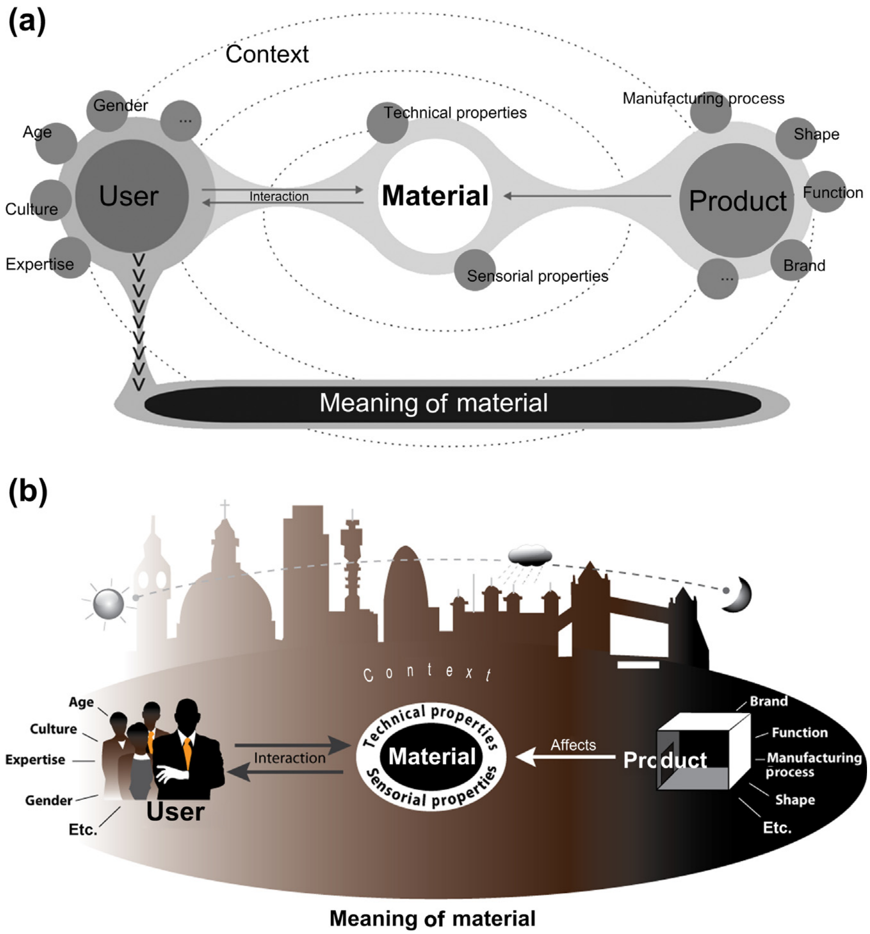


FIGURE 21.4
(a) Model resulting from Elvin Karana's research on the making of meaning for a material (© *Karana (2010:276)*); (b) Elvin Karana's model concerning the meaning of a material re-presented by Cheng-Siew Beh © *Beh (2012:140)*.

must be considered to be both propositional and experiential; skills both cognitive and psychomotor; and values both articulated and tacit. This position was presented visually at the Design and Technology Association's Millennium Conference (Norman, 2000) as shown in Figure 21.5. The capability of a designer or design team is bounded by the knowledge, skills, and values that they have or can access in order to resolve the design task. Education concerning "technology for design" can, and should, address all three of these aspects.

Materials technology for design

The discussion in this chapter has sought to illustrate a position in relation to materials technology for design. The nature of mathematical models demonstrates the need for both aspects of materials science

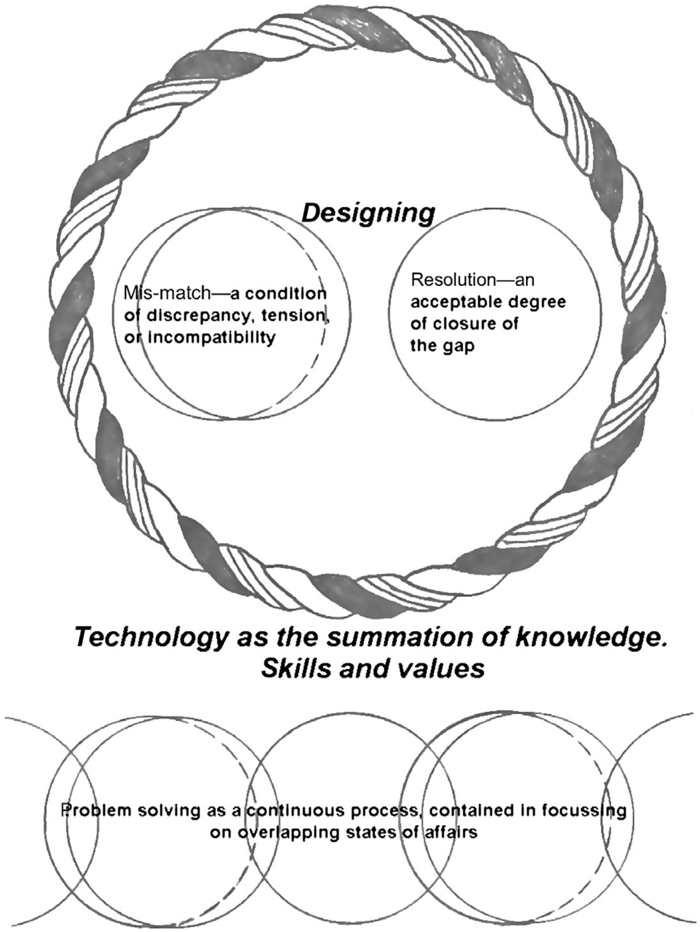


FIGURE 21.5
A model of technology for design as the summation of knowledge, skills, and values. © *Norman (2000:129).*

and practical engagement with materials to be important parts of design curricula. As ever, a major problem will be selecting which aspects are most appropriate for particular students, but whatever the design area the requirement remains. Design students must understand how to use mathematical models of materials, and an aspect of that know-how must be gained through experiencing materials in reality: in the workshop or in materials libraries. The potential of visual models to scaffold cognitive modeling and inform designers in handling complexity demonstrates the key role that they must play, and not least because of the persuasive power of visual media.

Appropriate design pedagogy might dictate that these aspects of materials technology are addressed "for designing" or "through designing" but they need to be embodied somewhere within the design curriculum.

CONCLUSIONS

The chapter has essentially returned to where it began. Designing as illustrated in Figure 21.1 requires interaction through all the senses between cognitive and external models. This is also the case in relation to engaging with materials technology for design. Mathematical and visual models of materials technology offer the designer tools for expanding their perceptual span, as well as the opportunity to misuse them. Models are by definition, not reality, and capture key aspects of it. The effective use of such design tools requires particular knowledge, skills, and values related to the materials being considered, which can be developed through direct experiential engagement.

Acknowledgments

Technology for design has been the focus of my career at Loughborough Design School and I am indebted to Loughborough University for the opportunity to become engaged with these issues. However, more importantly, I should acknowledge all the students—school, university, and research students—from whom I have learned a great deal during my teaching and research. Of course I hope that they feel the same.

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CHAPTER 22

From Stiffness of Iron–Carbon Diagrams to Weakness of Sensoriality: The Manifold Designerly Ways of Developing Engineering Competencies in Materials

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Politecnico di Milano

CONTENTS

Contemporary industrial design pits designers against a growing level of complexity of human, social, and industrial needs that are reflected in the design choices of any industrial product. In a setting such as this, the savvy use of materials in design not only solves the problem of the industrial project's technical functioning but also helps to define the characteristics of its personality.

The science and technology of materials is one of the fastest growing sectors of knowledge and development. Designers are offered an amazing number of potential materials (over 80,000) and transformation technologies (over 8000) (Salvo et al., 2001). Such a scale may be disorienting and lead to problems of "overchoice", as referred to also by Manzini (1986) over 25 years ago. At any rate, mastering the set of materials and transformation technologies (henceforth, we will simply adopt the term "materials" to also include the technologies of material processing), is fundamental for a successful design. It may even be the source of inspiration for the design itself. A shining example of this idea is the story of the Falkland lamp (Figure 22.1) that Bruno Munari designed in 1962 for Danese.

Materials Experience. http://dx.doi.org/10.1016/B978-0-08-099359-1.00022-9

FIGURE 22.1
Falkland lamp, 1962. Bruno Munari for Danese. *Photo courtesy of Danese srl, Milano. © Danese SRL, Milano, Italy.*

Munari himself said, during an open lesson at IUAV (Venezia, 1992): "*Quando sono andato in questa fabbrica di magliette per dire che volevo fare una lampada mi hanno detto che avevo sbagliato fabbrica… io voglio fare una lampada con un una maglia… -Ma no, non si è mai fatto-… ed io, ma sì!*".[1]

Training industrial designers about products, fashion, or interiors necessarily entails the transmission of technical skills. The final goal and presupposition must, however, be to stimulate their curiosity toward materials. These may become the source of inspiration for unexplored solutions or completely new products.

Solving Ashby and Johnson's (2002) dichotomy between technical designers and industrial designers, and their access to and use of materials, is the main training goal to be attained by materials and design educators at the undergraduate level whether through courses or supporting design laboratory activities

[1] "One day I went into a shirt factory to see if they could make a lamp and they told me that I went the wrong place… I want realize a lamp with thighs… No, it has never been realized – and I, but yes…" (this text has been reported by several authors as a Munari's visit to a hosiery. The recorded lesson (in Italian only) is available at the media center of IUAV (Venezia, Italy), and on-line at http://php.unirsm.sm/mediateca/web/conferenze.php?id=11.

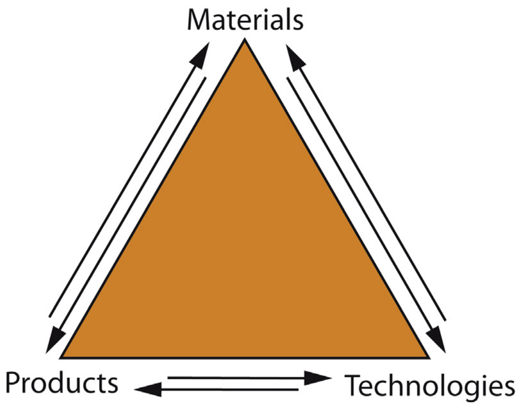

FIGURE 22.2
Mutual interactions between materials, technologies, and products as a characteristic concern in design. *Adapted from van Bezooyen (2002).*

at the graduate level. The baseline idea is to train future designers and provide the theoretical and practical tools for informed use of materials and technologies, so that graduates can eventually conceive of these as an opportunity in their professional projects. This process manifests itself in the designers' skill at overseeing the set of mutual interactions that take place between (1) the material, (2) transformation technologies, and (3) industrial products, based on the triangular interaction originally schematized by Aart van Bezooyen (Figure 22.2).

Figure 22.2 and the design implications consequent to it are the baseline of the educational approaches discussed in this chapter. Although these approaches appear clear and straightforward in the text as written here, they are actually the result of a lengthy process of iterations and improvements by teachers of materials and technologies. This process entailed the overall revision of individual courses, both in terms of contents and learning and teaching methods. The methodological facet is important for effectively transmitting the notions considered fundamental in the training process. This is also crucial in our experience because didactic methodologies definitely affect the structure and evolution of knowledge itself.

The conventional approach to transmitting technical knowledge to designers involves the definition and classification of all phenomena. Then it tries to derive the correct information in the appropriate form for the designer's use, from the applied knowledge of natural sciences. Constant contact with the academy by young industrial designers employed in various sectors (e.g. products, fashion, and interiors) has led to noticeable effects on the conventional teaching method of engineering—use of methods for transmitting knowledge that are more typical of industrial designers, and more in general typical of a "designerly" way of knowing, thinking, and acting (Cross, 2001).

Handling the complex aspect of design as a methodology goes beyond the goals of this chapter. Nevertheless, the methodological aspects of teaching materials when training industrial designers are the basic theme of the chapter. The following sections describe, according to our direct experience and perspective, the evolution of Materials courses where materials are taught at the Industrial Design

School of Politecnico di Milano; in particular, the structure of those courses, the attempts to modify the transmission of materials knowledge through those courses, their evolution, and a review of how the courses have grown.

Finally, we will discuss how an approach oriented toward thorough integration of the rigorous jargon of engineering with the jargon of design (linked more to perception and sensorial dimensions) opens up new opportunities for research, with potential to profoundly modify the methodologies of materials selection.

EDUCATIONAL PROGRAMS FROM THE TRADITIONAL LECTURE CLASSROOM TO THE INFORMED USE OF MATERIALS AND TECHNOLOGIES IN DESIGN

Students at Politecnico di Milano School of Design are recruited through a highly selective entry exam, which evaluates their basic competencies in understanding texts and logic and their grasp of basic science. The number of students is annually planned unlike other schools in the Italian public educational system. This process has become ever more selective as the School's prestige and importance have grown, leading to an average growth in the quality of students with regard to basic competence and motivation. Nevertheless, the discrepancy between the education these students receive from secondary schools, ranging from the classical lyceum to vocational training technical institutions, requires a considerable effort to bring all the students up to the same level. This is done through institutional courses when serious shortcomings are found in students' basic understanding, or within introductory classes in the curriculum. Such provision is also made for courses on materials, which are usually held in the freshman year. Fundamental notions that support teaching science are reviewed during the first year of materials classes (algebra, geometry, calculus, and physical scale).

Overall, however, the courses try to transmit a method for approaching problems that we call *Cultura Politecnica*. This approach is developed during the 3-year foundation level (leading to an undergraduate degree) and specialization training courses (leading to a Master's degree and/or a second-level Master's degree). The Politecnico di Milano courses summarized in Table 22.1 either comprise lectures or support sessions for the design laboratories that students are asked to attend during their studies and/or for final overview studio. The courses are given by individual teachers using a single-subject approach in the first year of curricula at the School of Design. When taught in conjunction with design studios, students benefit from the experiences not only of the university staff members but also industrial designers and other professionals from industry, who are somehow linked to the topic of investigation in the design studio.

It is easy to understand how the process of crossovers between materials and design influences teaching. The drive to adopt training models that differ from those commonly used by teachers with an engineering background may have benefited from the constant contact with teachers of differing training and background. To better understand the evolution in the materials and design training methodology and mind-set, we can revisit the diagram presented in Figure 22.2 and impose some coloring to indicate students' educational process, and the historical adaptation of the teachers. Upon entry in the design school, freshmen are strongly concentrated on the product (see Figure 22.3, where the orange coloring

Table 22.1 Structure of Material Courses at Politecnico di Milano, School of Industrial Design

		INDUSTRIAL DESIGN		DESIGN AND ENGINEERING	
LEVEL	Y	CORE	ELECTIVES	CORE	ELECTIVES
Bachelor	1	***Materials for Design*** 1. Materials Structure/properties 2. Materials selection criteria 3. Classes of materials			
	2	***Materials processing*** 1. Technologies 2. Mechanic			
	3	***Final Studio*** 1. Materials and technology 2. Materials databases	***Sensory, expression and materials*** ***Sensorial contexts in design*** ***Surfaces and Finishing*** ***Sustainable Materials***		
Master	1			***Materials for design*** 1. Advanced class ***Studio*** 1. Technology as constraint 2. Technology as possibility 3. Technology as opportunity	***Nanomaterials and Fuctional Materials***
	2	**Final Studio** 1. Materials and technology in industrial project		**Final Studio** 1. Materials and technology in industrial project	

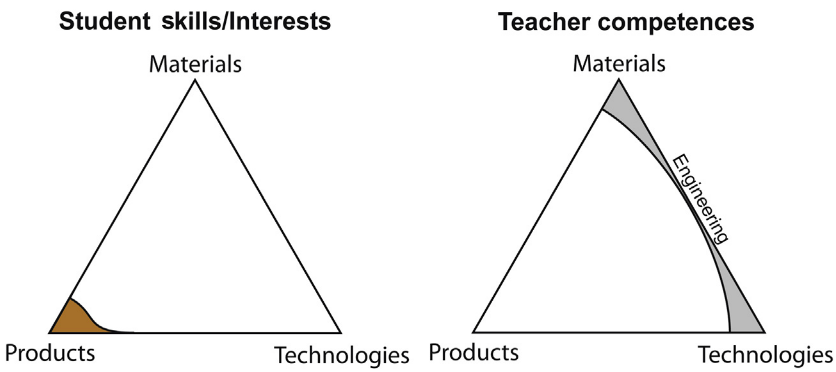

FIGURE 22.3
Competences and interests of freshmen versus the initial (historical and background) competences of teachers of material classes.

shows the interests/expertise of the students), almost with a fixation on it. For example, the fashion design classes are populated with young people who think they must design high-fashion clothing for upcoming collections, without having the very minimal perception of the complexity of the fashion design system.

Likewise, for teachers coming from a heavily engineering training, the predominant defining feature is competency in materials science and technical selection alongside technologies (alluded to by the stiffness of iron/carbon diagrams). Hence, the area in gray shown in Figure 22.3 comprises a viewpoint overwhelmingly oriented toward materials and technologies. In this sense, the process of aligning teaching competences with student interests (and vice versa, of growing interest in technological competences) follows parallel paths of temporal evolution and appropriateness of teaching levels.

Introductory classes at bachelor level of industrial design

The work done in introductory classes of Industrial Design bachelor program (Materials for Design, Table 22.1) has a twofold goal:

1. acquire specific knowledge about the properties of materials, correlated to their chemical and physical structures, and introduce some rudimentary tools for evaluating mechanical and structural characteristics in design. This last feature is directed toward the analytical selection of materials;
2. learn how to select materials, transforming design requirements into properties, and then restraints or goals, by recognizing the functions of product parts so that materials may be selected appropriately and analytically. In addition, in recent years, the issues of sustainability have been garnering special significance. They are presented as guidelines during the traditional lecture courses.

The idea at the first year level of education is to present students with the essential problem of materials selection connected to a particular product (Figure 22.4(a)). This didactic activity is basically split into two approaches with profoundly different teaching models:

1. a *deductive approach* linked to lectures on mechanical aspects, the structure of materials, and material classifications;

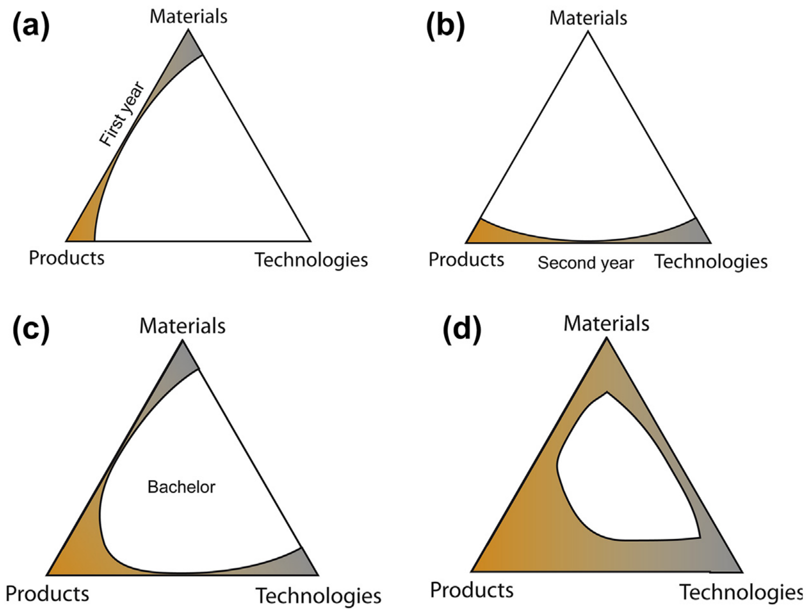

FIGURE 22.4

(a) First year educational aims: materials selection in industrial design products; (b) educational aims of the second year technology course: technologies for manufacturing industrial products; (c) competences at the end of undergraduate education; (d) student competence on completion of Master's degree.

2. an *inductive approach* based on analyzing the requirements of a yet-to-be designed object and choosing the materials (*this approach is used in the freshmen design project*).

Teaching the structure of materials and properties is conventionally linked to lectures essentially with an engineering method, although it is supported by different examples of application that are recognizable as industrial design. In particular, the first approach is based on the acquisition of some simple knowledge on the mechanics of materials and the scale of objects. Introducing simple examples, such as calculating the tipping point of Castiglioni's Arco lamp, is an effective way to achieve this.

The *freshmen design project* is a turning point in the teaching of materials and design fundamentals (during *Materials for Design* class). This project is set as the final module of the introductory course on materials for industrial design. It gives opportunity to students to "solidify" their knowledge, by applying what they have learned from across course modules. A design problem is presented and the students work as a class under the supervision of a tutor who guides the process. The students are pushed to "act" (and thus acquire knowledge), through which they become the "problem experts" and thus acquire the tools for solving the problem and conducting the process. This project's structure entails strong student participation: for the first time in their education, the students are asked to solve a problem through team effort. The structure is a simple one: real objects relating to their course of studies are proposed. For example, a chair's back for a product design course, or the temple of a pair of eyeglasses for fashion design. The students are asked to analyze the object's function, define its constraints, and make some simple mechanical calculation aimed at materials selection.

In a conventional design process scheme, we of course would expect to see students tackle the brief, concept, development, details, and final product specifications. The freshman design project does not ask students to deal with these activities in a conventional manner. Instead, information relating to the activities is partially supplied as problem data, so that students can focus solely on the task of material selection. One fundamental aspect of the freshman design project is that it has permitted a profound change in teaching for the first time, due to its activity-based learning characteristics. Starting from the course introduction, teachers involved in materials lecture teaching at Politecnico di Milano have modified the contents and purposes of their courses and accordingly adjusted their structure and teaching.

Technologies, elective courses, and support in studios at bachelor during industrial design bachelor

Undergraduate second year classes and thereafter are broken down into mandatory and elective classes. Students who wish to acquire even more thorough knowledge of materials for industrial products can do so by choosing electives where competence in the issues of sustainability, sensoriality, and the study of advanced materials, finishes, and surfaces can be gained. The set of electives in particular springs from new and emerging interests in materials and design research and teaching, which have affected the professional interests of the involved teachers.

Material transformation technologies

A course solely on material technologies is offered in the sophomore year (*Technologies and Structures*); this intends to transmit knowledge and competences linked to processes for obtaining industrial products. The course is structured into modules, each of which deals with the competencies needed to design industrial products with a reference to technical feasibility testing. The course offers students an introduction to the technologies used to industrially manufacture products. The goal is to help students make design choices that are informed by production problems. Studying manufacturing technologies starts with the general features concerning the main transformation processes, and progressively moves toward design issues. The main technologies for serial production of plastic and metals, welding semifinished products, and assembling components are discussed. Students learn technologies and grasp the mutual interactions with the product (forming, joining the parts, finishing the surfaces, etc.). The course's structure is entirely lecture based, although it uses application cases as examples to highlight the relevance of technological knowledge in product design and engineering. It continues to maintain a traditional engineering structure, all the same (Figure 22.4(b)).

After these two courses (*Materials for Design and Materials Processing*, Table 22.1), students are considered to have acquired the (rudimentary) theoretical and practical tools to select materials and technologies for a project, even if they are not always capable of deeply connecting their competences, as represented in Figure 22.4(c). Theoretically and schematically, students at this stage can understand the importance of choosing materials and technologies for a successful design, but they are still moving with scant awareness in the triangle of correlation between materials, technologies, and products. Students' viewpoints are still heavily weighted toward the product and still not much inclined to grasp the design potential offered through careful and creative materials and technology selection.

Electives

Material-related elective courses have been developed over the years and offered with growing interest from students. This interest is strongly correlated to the enthusiasm of knowledge transmission from the teachers involved. Four elective courses are offered, covering a variety of complementary topics: conventional issues (treatments and surface finishes); highly topical, advanced research issues (the sustainability of product materials and technologies); and sensorial considerations (the expressive-sensorial properties of materials for design, and sensorial settings within design). By taking these electives, the intention is for students to be able to back up their criteria for selection and choices, based on a combination of human perceptive features and analytical features that are proper to the science and technology of materials. This combination of supplemental competencies should allow expressive potential to grow, without forgoing the rigor of scale, fully respecting geometrical, structural, and functional constraints.

The process for the last of these topic areas—sensoriality—was initiated 10 years ago through Valentina Rognoli's doctoral dissertation (Rognoli, 2004), which was one of the first in Italy to intuit the importance of a hybrid approach to materials and design education, combining the eminently perceptive-emotional dimension of the designer with the analytical and quantitative features of engineering (Rognoli, 2010). The teaching proposal is well summarized in a passage by Le Breton (Le Breton, 2007)

> The significant penetration of the world of sounds lets piano tuners adjust various instruments, basing themselves on listening to the gradations between absolutely worthless notes, inaccessible to the unskilled, whose identification is made possible by especially refined knowledge and education. This learning introduces difference where passersby on the street perceive only a continuum that does not seem likely to lend itself to distinctions. Educating a sensorial capacity consists in taking what seems continuous to many who do not have the key to grasp its sense, and make it discrete, and enumerating the numberless differences of what seemed so similar at first glance. This apparent virtuosity arouses surprise in the unskilled, but it is the result of an education accompanied by a special sensitivity that heightens its subtlety.

The main result of embracing this approach was the commencement of a course offered to all students in their third year, so they could approach studying materials through the theme of sensoriality in all its multiple aspects, and according to a kind of inverted perspective on materials selection. Indeed, moving from the multiple dimensions linked to the expressivity of materials, the course accentuates the stimulating complexity of the emotional and perceptive setting, which decidedly influences the whole design process. This way, the course proposes methods for introducing tools for sensorial education in design, including proper knowledge of the different jargons about materials and the proposal of a sensorial atlas. The atlas aims to rationalize the study of expressive and sensorial properties, which are traditionally classified by sense (e.g., photometric and tactile properties). Adjective opposites are introduced to students to garner first-hand appreciation of the analogous scale of properties (e.g., light/heavy, hot/cold, transparent/opaque, and shiny/matte). Finally, the atlas is used to introduce students to a chemical and physical relation to their material experiences (e.g., density, conductivity, and index of refraction). It also outlines the use of tools for measuring expressive-sensorial qualities quantitatively, so that they may be translated into properties that can be recognized by science and engineering. To this end, the course develops a language of materials that appears more shared at the end of the course, directed toward new user-centered criteria for selecting product materials (Rognoli, 2005; Rognoli and Levi, 2011).

Senior project at bachelor

In order to graduate, students are asked to participate in a final studio where they must manage the design of an industrial product. Materials and technologies once again find their teaching space and support for design even in this studio. The knowledge developed over the freshman and sophomore years are placed at the service of the laboratory (studio) through a technological support from teachers and mentors, where the teacher emphasizes some fundamental concepts (about the design that must be completed), and supplies guiding support. Two tools are also presented in this laboratory, which is now a consolidated part of training young industrial designers: (1) methods for selecting materials, in some cases these have been updated to technologies with special reference to the analytic method, and (2) Granta Design's CES Edupack and its associated property charts that provide an overview of the ranges of material properties and serves as a selection tool for choosing materials to meet given design constraints.

The approach of the design laboratory (project studio) is clearly design driven, making it possible to transmit and finalize the basic knowledge that students need at the end of an undergraduate course, namely, a "materials perspective" and the methods, tools, and understanding to enable the rational selection and use of materials (Ashby and Johnson, 2002).

Master competence

During the first year of the Master's course (fourth year of university training), students are exposed to a highly demanding design studio. The studio is structured into three activities, and students gain a growing amount of knowledge about using materials and technologies within them. The course's teaching is structured in a process that calls for three exercise phases, each of which has the task of exploring a viewpoint about the connection between a product, materials, and technologies. The exercises are a moment to use the design process models and tools, partially transmitted within the course itself. The sequence of the exercises is conceived to introduce progressive levels of complexity. This laboratory's structure reinforces the idea of pushing the student toward technologies and materials as opportunities, starting with the convention that this is a constraint. The course is structured into three parts:

1. "Technologies as constraints". The starting point comprises a material and a technology associated with an applied theme with its own constraints. Students are asked to use the material/technology given, correctly and consciously, to deal with the application issue proposed. They learn how to understand technological constraints, the skill of stating requirements precisely, and the capacity to guide the definition of a product's characteristics, starting with a set of requirements.
2. "Technologies as possibilities". The starting point is a design issue and the students are asked to choose the most appropriate material/technology to solve the problem itself, based on the design choices made. In this sense, it pushes the level of awareness of using materials to a higher level,

linked to the capacity to apply criteria for choosing materials and technologies based on project requirements (Figure 22.4(d)).

3. "Technologies as opportunities". The starting point is a material/technology combination. Students are asked to explore the possibilities of using the combination to develop a paradigmatic design application, understanding technological constraints, and exercising skill in stating requirements precisely. Students learn the skill of governing the process of defining a product's characteristics, starting with a set of requirements, the skill of applying criteria for selecting materials and technology based on design requirements, the skill of building up scenarios for application or transfer of materials and technologies, and the skill of developing application solutions.

This studio proceeds simultaneously with a course in "Materials and Technologies for Innovating Industrial Products". During this course, knowledge about materials and technologies is introduced in an advanced manner. This runs in parallel to lecture and laboratory courses, not having emphasis in materials, making it possible to implement three features that we feel are fundamental for teaching materials and technologies: (1) complement the deductive learning method with an inductive method, with obvious advantages deriving from both; (2) explore teaching content and knowledge horizontally in breadth (where ample knowledge is transmitted during the integrated course), and vertically in depth (knowledge in the laboratory courses is deepened, although it is partial because it is "circumstantiated" by the product developed); and (3) develop a theoretical/practical relationship.

The teaching experience of this studio fully manifests how the educational process leads the student to greater awareness (Figure 22.4(d)). After their Master's degree, students should have a level of awareness that can lead them to take advantage of materials and technologies as design possibilities. As a school, the nurturing of this awareness has driven us to evaluate the opportunity of pushing further beyond training, with a Master's degree in the Science of Design Engineering.

Combining mind-sets: design engineering

Chronologically last in completing the materials education portfolio at Politecnico di Milano is the Master's degree in Design and Engineering. This degree is one of the first examples of an "intramural" course proposed by teachers coming from the schools of Design, Material Engineering, and Mechanical Engineering. It is suited to graduate (Bachelor's) students in both engineering and design subjects who are strongly motivated to open themselves up to a deeply and concretely interdisciplinary education.

The Design and Engineering Master's program aims to train designers to combine their design approach with a technical-engineering approach, so that they are capable of designing and developing a product in a comprehensive manner. Thus the program develops the theme of material expressivity and material valences, alongside technical and operational implications concerning the handling of manufacturing processes. It also develops capability in supplying a complete design procedure, from the product concept, through the definitive and final specification design, to the drafting processes needed to put a product into production. Graduates of the program have special competences in choosing materials, in design methodologies in the virtual environment, and in the effects of technological features of manufacturing systems on product design. The goal of the cooperation between the three different subjects on design education here is to specialize training in three fundamental areas, one of which is specifically devoted to materials.

This program covers specific awareness and operational skills in materials, surfaces, and the technologies necessary for their realization. It once again combines the two mind-sets of engineering and design, through a profound and aware understanding of the relationships between a structure (product), its physical/mechanical/functional properties, and its sensorial/perceptive/emotional properties. Studying and designing new application potentials even based on behavior during the exercise phase are indeed one of the main foundations of this program. Students are trained to understand the interaction between materials, settings, and the quality of use of a product, and to be able to manage that interaction. This educative path is based on the idea that future designers should be able to develop a pleasant, attractive product that is also practical and functional.

This offering in education calls for the construction of a theoretical foundation through lectures, on which to apply methodologies of creative design and product development in the laboratories, and on design issues that are highly topical in terms of technology for process and use. The origin of students from different majors makes it necessary to provide first year teaching courses considered to be fundamental for raising all students to the same level and to mutually complete their knowledge of industrial design and engineering. Second year lectures are oriented toward acquiring specific technical knowledge to develop a definitive and final specification design, as well as further investigations into the design mind-set (through electives and humanities subjects). Both years of the Design and Engineering Degree involve design laboratories: they are oriented to applying the knowledge supplied during theoretical teaching and to the integration and application of different approaches to materials selection in real design cases. The latter are fundamental for acquiring advanced skill at making mature, informed choices.

THE INVERSE PERSPECTIVE: "DESIGN DRIVEN" MATERIALS RESEARCH

We have encountered new technological problems linked to materials, often arising from needs or requirements in the industrial world. In response, we have structured materials-related courses, and driven their evolution over the years as a mark of a new specialized education process. In this sense, research contracts with design sector companies have helped us face the typical problems that industrial design itself has when developing new products and technologies. In some cases, this has driven our research teams to deal with new technologies; in others, with unexplored problems. While performing these activities, ideas have arisen on how theoretical and application-based tools developed during the research may be best used in teaching (Rognoli, 2010). Vice versa, the designs developed by students, especially those linked to the Master's thesis, can help further develop new research lines or open them up, echoing what we have witnessed happen in companies. In this sense, the idea of a *designerly way of learning turns into a designerly way of conducting research*.

Some examples of significant developments and designerly materials research during the teaching process have included research collaborations with major "Made in Italy" companies, for example, in the textiles and clothing sector. One especially important case was financed as a trio by a major Italian corporation, a leader in the clothing sector, and by the Ministry of Universities and Research. The point of departure was content within the undergraduate course on expressive-sensorial characterizations of materials: the study involved development of new approaches to quantifying wool pilling, as well as measuring the "hand" (feel) of fabrics. Both these subjects of interest led to the proposal of new, simplified methods for measuring the complex mechanical properties correlated to the formation of fabric pills and the perception of a fabric's "hand".

CONCLUSIONS

In this chapter, we depicted the structure of courses and laboratories concerning education of Materials of Industrial Design students, at both Undergraduate and Master levels, according to our experience and contribution at Politecnico di Milano. The historical evolution of this structure and its present articulated didactic path reflect a comprehensive evolution in teaching models and formative goals. Students are able, by following the presented step, to acquire a conscious use of materials (and production processes) in an industrial design project, ranging from the rigorous application of selection criteria to the exploitation of potentials related to material properties. Alongside the didactic aspects, which evolved from a traditional engineering teaching experience to a designerly way of teaching and learning, scientists and professors involved in this process, during the last 20 years, evolved their research activity in a *designerly way of conducting research*. Beside the continuous improvements in teaching activity, the unexpected results in the way of conducting research offered us the chance to support new research scenarios.

This represents a continuous challenge: overcoming the boundary between the two fundamental disciplines of education and research; supporting the efforts of teachers, researchers, students, and consumers; and driving real sustainable product innovation through any crisis.

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CHAPTER 23

The Concept–Context Approach to Learning Material Properties in Design(-Related) Education

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CONTENTS

Although designing is a practical activity, it entails a lot of conceptual work. Customer requirements are related to concepts like usability, functioning, and efficiency. Technical specifications are related to concepts like weight, size, and shape. Many design considerations are therefore on a conceptual level. Therefore, learning to design also means learning concepts and how to reason with them. Learning concepts does not only happen in design education. Almost all learning in schools, colleges, and universities to some extent is the learning of concepts. Design education has a special challenge in that the concepts that are to be learned are in quite different domains. In physics education, all concepts are in the domain of physics, and although that, of course, is not a uniform domain but has many subdisciplines with quite different characteristics, all concepts in physics do have a certain communality in that they are all related to natural phenomena. Likewise, in language education, all concepts that are to be learnt, like verb, article, and noun, are related to language.

Design, however, is concerned with concepts from at least two very different domains. On the one hand, there is the domain of science and engineering (if, at all, that can be seen as one domain), and on the other hand there is the domain of social and human sciences (if, at all, that can be regarded as one domain). The first-mentioned domain is related to the technical aspects of the design work and the second domain is related to the human and social aspects of the design. The selection of materials in design is directly related to both domains. The heart of the challenge of selecting the best material is to find a material that has the right physical properties (I will use that term to indicate both properties that are studied in physics and in chemistry, and in cases of living materials in biology) that allow the design to fulfill its desired function. As a consequence, selecting materials in a sophisticated way means

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knowing about both physical properties and functional properties. It is also necessary for a designer to be able to sharply distinguish between the two. Smoothness is a material property that can be present in a design. A customer, when asked for requirements may answer: I want the product to look smooth. What in fact happens then is that the customer answers the question by providing a physical instead of a functional property. A designer has to be so well acquainted with concepts that he or she is able to recognize what happens and reach a better solution by asking the customer why he or she wants the product to be smooth in the first place. When the customer answers that next question by saying: "I like that for its beauty," the designer knows that perhaps there are ways of fulfilling the aesthetical requirements other than by smoothness and thus widens the range of materials that can be selected. Conceptual insight in this case can be the key to an optimal solution because a confusion of concepts is recognized and solved. So the teaching and learning of concepts related to materials selection is very important in design education at all levels. Concept learning is, however, difficult, as a long tradition in education has shown. In the next section, we will see how our ideas about teaching and learning concepts have shifted in the course of that tradition.

CURRENT EDUCATIONAL THEORIES ABOUT TEACHING AND LEARNING CONCEPTS

Originally, educators have believed that it was possible to teach concepts at an abstract level directly. Concepts are by definition abstract entities. By leaving out certain aspects of entities, concepts can be derived from reality. When we see a table in a room, we can leave out all functional aspects and focus on the physical aspects only. We can further narrow our scope by only looking at the mechanical properties of the table. Within that range, we can further narrow down to one property, namely, the one that described how easy it is to turn over. Thus, the abstract concept of stability emerges from the concrete entity (the table). In education, there was a time when we believed that we can immediately confront learners with a concept like stability. We would then give a definition of stability and only later illustrate that by tables being turned over or other practical phenomena. There are learners for whom this works, but they are only a subpopulation of all learners. Not all learners are able to grasp the meaning of the definition taught at an abstract level directly, not even if supported by some examples. Also, they have difficulties applying the abstract concept in concrete cases. This type of education can be called deductive, because learners have to draw conclusions about particular cases on the basis of considerations about general rules (see, e.g. Felder and Silverman, 1988). For instance, they have to make a judgment about the stability of this particular table after having learnt the general definition of stability. Going from general (abstract) to particular (concrete) then is a reasoning step of deduction. As stated before, this does not work for all learners.

Educators have therefore shifted their ideas about concept learning toward the idea of learning by transfer. Teaching then starts with a practical case, from which abstract concepts are derived. Students get to see a table, experiment a bit with it, and at a certain moment the step toward the abstract concept of stability is made by the teacher, or perhaps by the learners themselves with the teacher's guidance and support. Then the learners are asked to apply the same concept to a different case. This is called transfer. The use of the concept shifts from one case to another. The expectation was that the concept would thus become versatile in the learner's mind. He or she is able to shift between cases using the same concept to deal with new situations. This, however, still appeared to be too optimistic an approach for many learners. Educators have, therefore, taken a next step in their thinking about concept learning. They now believe that for learners to be able to grasp the meaning of an abstract concept, it is necessary to see it in a variety of cases first and then gradually (inductively) to derive the concept from the range of situations they were confronted with. Within the contexts, authentic practices should be identified that learners can identify with and that will allow the creation of educational settings in which learners perform practical activities that enhance conceptual learning (Bulte et al., 2006). Authentic practices are real practices that have not been made up for educational purposes but are part of the students' lives. Of course, they are adapted for educational purposes when used in class. Examples are traveling from home to school, playing sport in leisure time, and visiting a doctor or hospital.

A metaphor that can help one to understand the learning difficulty in concept learning and illustrates the need for dealing with the concept in a variety of concrete situations first, is the following. Concepts are like chameleons. We can define a chameleon as lizards that have parrotlike feet, separately mobile and stereoscopic eyes, long and rapidly extrudable tongues, and some more external features. Learning the concept of a chameleon in a context would mean seeing one in, for instance, a grass field. But that would give the impression that chameleons are green. One could easily be mistaken by denying "chameleon-ship" to the same creature sitting near water and having adopted a blue color. For a person who does not grasp the concept of a chameleon, it is difficult to separate those characteristics that define a chameleon and those that are not essential for chameleons but context-bound. It is only when one has seen the green chameleon in the grass field, the blue one near the water, the gray one on a paved street, and the red one sitting on a red tile that one begins to recognize the communalities between all the chameleon appearances and separate them from what was specific for each context. It is by no means to be taken for granted that learners have the abilities to recognize the essential features of a concept by meeting examples of it in different contexts. Educational strategies are needed to help them gain this understanding. Such strategies must acknowledge the fact that abstract concepts always take different shapes in different contexts and therefore, as it is nowadays expressed in educational theories, cognition is "situated". As a consequence, learning can best take place by putting the learner in a concrete practice in a sort of "cognitive apprentice" role (Hennessy, 2008).

Another important notion that has emerged from many years of educational research is that concept learning is always a matter of reshaping mental images. Even before we start teaching about the concept of stability, learners already have certain beliefs about that in their minds. They may think, for instance, that heavier objects are always more stable then lighter objects. Such beliefs are usually formed by going through a range of practical experiences in daily life. People see many light objects turn over and many heavier objects staying straight up. The range of these experiences is limited and therefore such beliefs may be incorrect. Widening the range of experiences may correct some of these beliefs. Becoming acquainted with the accidents with some huge ferryboats may cause people to rethink their beliefs about the stability of heavy objects. Even extremely heavy objects appear to be potentially very unstable. But without such a widening of experiences, some incorrect beliefs can become very stuck in people's minds. We know, for instance, that most young people believe that objects will always come to a standstill when no force is exerted on them. In physics education, they are told otherwise: when the total force exerted on an object is zero (Newton), the object will continue to move as it does. This is in conflict with the learners' intuitive ideas and this makes it difficult for the learner to understand

Newton's concept of force. In order to make this learning happen, we have to create mental conflicts between what learners believe intuitively and what happens in reality. The confrontation with the sunken ferryboat is an example of such a mental conflict for those who always believed that heavy objects are always stable. For education, this means that it is important to get to know the learners' intuitively created beliefs in order to be able to create the necessary mental conflicts between these preconcepts and the more sophisticated professional or scientific concepts. Also, we have to acknowledge that these preconcepts do often work well in limited cases (usually the ones in which the learners had initially got to know them) and therefore the term "misconception" that is often used in this context is not entirely proper. But as these "misconceptions" do not match with the more generally applicable scientific concepts, in this chapter I will also use this term sometimes to indicate the learners' naive or preconcepts.

We will now see how these educational developments apply to the learning of concepts related to the selection of materials. First, we will see what educational studies have learnt about preconcepts related to materials, then we will consider how appropriate mental conflicts can be created that stimulate learning of the correct concepts and how a concept–context approach can be elaborated that puts this in a curricular perspective.

PRECONCEPTS RELATED TO MATERIALS

Although the number of publications about preconcepts in the engineering and other design-related domains is still small, there are studies that give us an impression of the sort of preconcepts that can be found with learners. In particular, we find studies among younger learners and college students. It is well possible that some of the preconcepts that were found among younger learners linger on during the educational path they follow. This is likely when these preconcepts are not challenged either by (educational) design or by (daily life) accident.

A study among 92 students in elementary schools in Australia by Davis et al. (2002) showed that these children at that age level have difficulties in distinguishing different material properties. For instance, they easily mix up strength and other properties such as specific gravity (often named "weight" or "heaviness" of the material by them). Also, hardness and breakability were found to be confused. Students also had difficulties comparing two materials based on the same property (e.g., strength). Some improvement was seen in older children compared to younger children. This development suggests that a more abstract concept of "strength" that allows for comparison between two materials emerges over the years with students. But the study shows that it is not to be taken for granted that all learners understand a priori that different materials can be compared based on general, abstract concepts such as strength and other material properties.

A study among science teachers in the United Kingdom by Pine et al. (2010) revealed that science teachers can add many more misconceptions among elementary school children. According to the teachers, some children have difficulties recognizing that there are more materials than wood and metals, others see only textiles as "materials", again others mix up steam and smoke, and in general children have difficulties in realizing that water, steam, and ice are different manifestations of the same material.

Krause et al. (2003) used a materials concept inventory to assess conceptual gain in introductory engineering materials courses and found many misconceptions with students before the courses (particularly in the domains of chemical properties, electrical conductivity, and plastic deformation). Also, Kitto (2007) discovered several fairly fundamental conceptual problems in understanding materials with engineering students (for instance, they could not well distinguish between products that require high tensile strength materials from products that need materials with high toughness values). This shows that, even though university students may not any more have the basic conceptual difficulties that were found with young children, this does not mean that they do not have misconceptions at a more sophisticated level.

What we see is that preconcepts deviating from what we have accepted as scientifically correct concepts can be found in all age levels, be it that the most fundamental misconceptions seem to diminish with increasing age. This underlines that it is necessary at each level of education to investigate what preconcepts concerning materials and their properties may be present in order to deal with these properly. Ignoring them will only result in creating a "school image" that will exist next to the "street image" as long as the "street image" is not challenged by conceptual conflicts.

A specific issue I want to address here is the relation between physical and functional properties. In order to be able to choose the best material in a design challenge, learners must learn to identify relations between what can be called the physical and the functional natures of the artifact to be designed. The physical nature then consists of all the properties that are inherent in the artifact, in particular the geometrical, physical, and chemical properties. The functional properties are relational as they require a user who ascribes possible functions to an artifact (hopefully including the one that the designer had in mind when he or she designed the artifact). In fact, design is finding an appropriate physical nature that allows realization of a desired function. In the philosophy of technology, this "dual nature of technical artifacts" idea was developed at Delft University of Technology (Kroes and Meijers, 2006). To be able to find that physical realization, designers must have knowledge that links physical nature properties and functional nature properties (in other words, they have to know

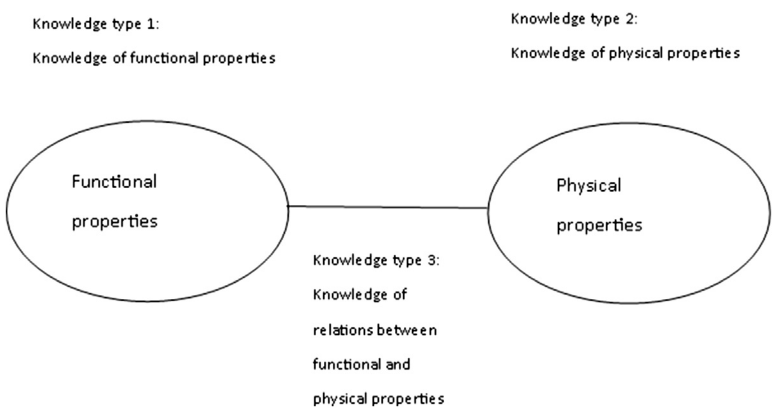

FIGURE 23.1
Three types of knowledge related to artifacts.

that material has certain physical properties P that make it suitable for realizing a certain function F). This knowledge is a third type of knowledge next to knowledge of the physical nature (e.g., the specific weight of water is 1 kg/l) and knowledge of the functional nature (e.g., an "all-in-one" printer can print, copy, and scan) (see Figure 23.1). Here, too, we find a whole field of possible learning difficulties. Frederik et al. (2011) investigated science teachers' abilities to relate material properties to functions of unknown technical artifacts. They found that many teachers had difficulties distinguishing between artifact properties (such as the physical properties of the materials they were made of) and the functional properties of the artifacts. This shows that even though people over the years may learn to identify physical material properties in artifacts, they do not necessarily also know how to relate them to functional properties.

CREATING COGNITIVE CONFLICTS

How can cognitive conflicts be created between incorrect preconcepts and the proper concepts that are to be learnt? I want to argue that design activities are very suitable for that. In a not yet published study among Dutch secondary school students going through a design challenge organized by the Delft University of Technology, students were first taught some basic concepts concerning the hydrodynamic properties of simple boats. A pre–post text assessment revealed that not much progress had been made in understanding the concepts. However, after the students had gone through a design challenge in which these concepts had to be used for designing a simple boat, there was substantial increase in understanding these concepts. This experience is confirmed by literature. A similar outcome was found by Hong et al. (2011) for 40 college students in Taiwan. They found that design activities (including drawing activities, as in the Nelson, Martin, and Baldwin study) enhanced the learning of material properties. A possible explanation for this can be derived from a study in elementary schools done by Nelson, Martin, and Baldwin. They used a sample of 117 children in US elementary schools to investigate their ability to design with the use of knowledge about materials. As a part of this study, these children were asked to identify "things made of wood" among a variety of objects made of different materials. It was found that there was a relation between the children's ability to draw the object and the correct identification of the material of which the object was made. The researchers concluded from this that "children who have been nurtured in their artistic endeavors will also reap benefits in other cognitive areas" (Nelson et al., 1998). This indicates that design activities that by nature include creativeness also stimulate cognitive development to which belongs also conceptual learning. But I believe there is another reason why design activities have that effect. Although this has not been studied explicitly, my hypothesis is that the design activity allows learners to experience that artifacts based on incorrect concepts do not work (properly/effectively). The experience of failed designs forces learners to rethink their conceptual understanding and be open for the possibility that the world works differently than they thought originally.

In a constructivist teaching approach, the learners' preconcepts are addressed in the pedagogical strategy in order to prevent the "street image" to continue to exist in the learners' minds. Kitto (2008, 2010) studied the impact of a constructivist approach on learning about materials at the university level and found that it appeared to result in good concept leaning. She found numerous misconceptions about materials and their properties (e.g., that metals have either covalent or ionic bonds) before a Materials

Engineering course taught in a constructivist way, and many of these had decreased or disappeared afterward. A study by Klahr et al. (2007) showed that even the use of virtual materials and artifacts in a design activity can make materials concept learning work. The use of simulations can apparently cause experiences of conceptual conflicts, just like the use of real materials and artifacts can.

A CONCEPT–CONTEXT APPROACH FOR LEARNING MATERIAL SELECTION

Potter (2011) did a qualitative study among experienced designers and showed that in particular the experience of applying the materials in specific contexts helped them to develop a sound understanding of the materials. This supports the idea of contexts as a useful pedagogy for teaching about materials in design(-related) education. This study is an example that suggests that the general ideas we hold nowadays about conceptual learning (see Section Preconcepts Related to Materials) also work for learning about materials in design(-related) education. In the concept–context approach, the use of contexts is the very basis of concept learning. The curriculum is then to be constructed from a combination of concepts to be taught and contexts in which they can be taught. This can be represented in a matrix structure with the concepts in the rows, the contexts in the columns, and particular situations within the contexts in which the concepts can be recognized (De Vries, 2011). For instance, one of the material-related concepts in the rows can be strength and one of the contexts on which the curriculum is based can be household equipment, and then in the cell combining this row and column, designing plastic cutlery can be an activity that allows learners to enhance their understanding of strength as a property of plastics in the context of household equipment. Later, the same concept will be taught in a different context, for instance, transportation means (e.g., by designing a frame for a new type of bike). By getting acquainted with the same concept of different applications (contexts), learners will deepen their understanding of the concept and the concept will become more versatile in their minds. Also, the concept will become part of a larger network of concepts because a variety of contexts will allow learners to relate the same concept to a variety of other concepts.

CONCLUSION

In this chapter, I have argued that learning about materials in a design context should make use of current educational insights. Such insights include the existence of preconcepts in the learners' minds and the need to address those in creating conceptual conflicts so that learners become willing to change their naïve beliefs and move toward accepting the more proper scientific concepts. I have used existing studies in literature to show that these general insights also apply to the area of materials in design. In the concept–context approach, learners are confronted with the same concept in different contexts so that they get to know the concept in a more in-depth and versatile way, and in order to embed the concept in a network of concepts that also provides insights into relations between concepts. It is desirable that educational research is done to investigate how this approach could best be realized: what contexts are suitable for learning what concepts and what authentic practices can be used for that? This kind of research would support a sophisticated curriculum development for design(-related) education in which the learning of material-related concepts will flourish.

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CHAPTER 24

Materials Selection for Product Experience: New Thinking, New Tools

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CONTENTS

Successful product design is characterized by an end product having qualities that seamlessly attend to users' functional as well as hedonic needs (Hassenzahl, 2003). Functional needs broadly determine the need for people to achieve a goal or task with a product in an efficient and usable way. Hedonic needs broadly determine the need for people to "feel good" about products, which if we use Sir Terence Conran's words, can be regarded as "*objects of desire which are a pleasure to own, a pleasure to use, and a pleasure to behold*" (1993).

The achievement of functional and hedonic synergies unsurprisingly requires the contributions of a wide range of professions, and may include teams that encompass industrial designers, interaction designers, ergonomists, mechanical engineers, electrical and electronic engineers, production managers, and so forth. Within this mix of competencies, it is usually the prerogative of industrial designers and engineers to materialize product ideas. That is, to take a design from a conceptual or virtual state to a state where it can be realized as a physical artifact with certain combinations of materials, finishes, shaping processes, and joining methods. While engineering teams typically attend to the product–product (i.e., intercomponent) interactions and "working" systems of a product (Ashby, 1999; Jee and

Materials Experience. http://dx.doi.org/10.1016/B978-0-08-099359-1.00024-2

Kang, 2001; Johnson et al., 2002; Sapuan, 2010), industrial design teams typically determine the user–product (i.e., outward facing) interactions and overall visual identity and user experience of a product (Desmet and Hekkert, 2007).

The differences in professional remits between engineering and industrial design unsurprisingly result in different ways of knowing about—and utilizing—materials. However, sensitivity to these differences is often difficult to detect. Ashby and Johnson (2002) were notable in initiating a shift toward human factors in product materials selection, exposing how selection activities are practiced as "art" (for product expression and aesthetics) as much as "science" (for product performance and utility). In today's era of designing for product experience, it is not adequate to perform formal materials selection activities solely on the basis of technical requirements and engineering data. Technical accomplishment is just one design criterion among a much larger spectrum associated with contemporary materials selection: materials can please our senses, suggest things to us and affect us emotionally, in addition to performing important functional roles.

> …if the designer changes the product's material – let's say from aluminium to plastics – this change has consequences for its tactual and visual aesthetics, for the symbolic and social meaning attached to the product, for the emotions it can elicit, and for its durability, reliability and performance. Hence, this decision affects the way the product is experienced in multiple ways, and it will ultimately affect the quality of the life experience this product is supposed to support.
>
> **(Schifferstein and Hekkert, 2008)**

Despite the necessary duality of product function and expression, the majority of available materials selection advice and resources is directed at supporting functional product decisions—that is, for helping determine which materials can satisfactorily meet the technical demands on a product, such as high strength, high stiffness, and low weight. It soon becomes apparent that industrial designers—who are heavily concerned with product suprafunctionality (McDonagh-Philp and Lebbon, 2000) or *designing beyond function*—are poorly served with materials selection information and tools, while their engineering colleagues are well served with systems such as the Cambridge Engineering Selector (Granta Design, 2013).

USER-CENTERED MATERIALS SELECTION

What differentiates engineering and industrial design perspectives on materials is the centrality of the user for the latter perspective. It is not just a matter of materials interconnecting with other materials: it is about users' perception of, and interaction with, material–product combinations.

To elaborate by means of an explanation, in Figure 24.1 four citrus juicers can be seen, each made from a different material family (ceramic, metal, plastic, and glass). Each juicer is a currently marketed product, capable of performing the essential function of juicing citrus fruits. However, each will have its supporters and detractors, because of the materials and manufacturing processes used and because of the sensorial qualities of those materials that combine to create a product that has a certain appeal (or lack of appeal) visually and in use.

FIGURE 24.1
Citrus juicers manufactured from four different material families: front to back, ceramic, glass, metal, and plastic. © *2013 Owain Pedgley.*

From this follows several questions. Why are people attracted or repulsed by products in certain materials? What drives their material reactions and experiences? And, how can we be sure to select materials that people will love, and avoid those they will hate? These kinds of questions demand what may be termed a "user-centered" approach to materials selection. That is to say, an approach that keeps foremost in the mind the desired and predicted experiences of users. So in the case of a juicer, the material-influenced product experiences may be associated with functional user needs (e.g., effective extraction of juice and easily cleaned surfaces) or hedonic user needs (e.g., visual unity when stored adjacent to other kitchen utensils and satisfying sound of juice dripping into the container when juicing). It will be appreciated that user-centered materials selection cannot be reduced simply to matters of visual aesthetics. Far from it, aesthetics of interaction is a central concern, while the complexity of the multifaceted issues involved can be quite daunting to organize and respond to.

In an attempt to explore how approaches to user-centered materials selection may be taken, the author commissioned articles for a special dossier on "futures for materials and industrial design education", published in the *METU Journal of the Faculty of Architecture* (Pedgley, 2010a). The journal brought together the work of five academics in the formative stages of their careers, each contributing to the growing area of materials education for industrial design, and each basing their work on new research and thoughts in the field of product experience (Karana, 2010; van Kesteren, 2010; Pedgley, 2010b; Rognoli, 2010; Zuo, 2010). The general emphasis within the articles was empirical research and pragmatism of application. It is notable that each contributor completed his or her PhD in the area of materials and industrial/product design, rather than materials engineering or materials science (Karana, 2009; van Kesteren, 2008; Pedgley, 1999; Rognoli, 2004; Zuo, 2003). Collectively, the contributors possessed considerable expertise on the limited provision of materials selection advice for industrial design. Although all the contributors carried out their PhD research in Europe, they continued their careers at institutions and firms in the Netherlands, Italy, China, and Turkey, helping to bring a global perspective to the issues raised. The aims of the special dossier were stated as follows.

- To identify the most important subjects influencing materials selection in contemporary industrial design, and to explore how those subjects may be best integrated into design education.
- To disseminate critical new thinking on materials and design education.
- To refresh the materials and design education agenda and stimulate debate.
- To bring together into a single source contributions from researchers who are influencing the materials education of new generations of designer.

A content analysis of the five articles was previously made for a design education conference (Pedgley, 2011). In the following sections, the content analysis is revisited to extract findings that relate to user-centered materials selection in design practice more generally, rather than design education specifically. In either case, the aim was to identify and map out a shared perspective on what the essential components of user-centered materials selection may be, and how those components may be intelligently structured. Despite differences in use of terminology by the contributors, five shared principal themes could be identified, which will shortly be presented: materials as a user interface, sensorial-expressive language of materials, samples and product exemplars, contextual considerations, and new materials selection tools.

Materials as a user interface

The first theme is a growing trend to view product materials as a contributor to the total "user interface" of a product. By this, it is meant that materials can affect the interactions we have with a product in a similar way that interactions are influenced by choices of buttons, controls, displays, and so forth. This is especially the case for products that are held continually or considerably during use, or which have a high degree of interactivity. Thus, the *sensorial qualities* of materials become of paramount importance when we regard materials as part of the user interface, and manifest predominantly as the "skin" of a product that outwardly communicates to its users (Boradkar, 2004), although we should be careful that this perspective does not develop into a superficial view of materials and material properties: materials still have inner matter. All the contributors identified sensorial information as the fundamental building block for influencing users' experiences of a product or for creating "sensual" impact (Folkman, 2010). In other words, they agreed that materials could (and should) be regarded as sensorial items.

Sensorial-expressive language of materials

The second theme acknowledges that if there is to be a shift toward the consideration of material sensorial qualities, then new forms of information and new "designerly ways" (Cross, 2006) of expressing material properties are needed. What is significant here is that this represents a departure from the way that material properties are classically categorized, according to quantifiable and testable properties chiefly used to determine technical performance. If we are to take a user-centered approach to materials selection, the language of materials that we adopt must be appropriate. For example, aside from using engineering language (e.g., a Shore D value of 75, a coefficient of friction of 0.04, or a yield stress of 500 MN/m^2), a sensorial-expressive language should be developed. This could be very colloquial, referring to materials used in well-known products (e.g., like an iPod, like Oakley sunglasses, and like a bicycle seat). Or, it could reveal direct comprehension of sensorial information (e.g., bendy, strong, slippery, and stretchy). Appropriate means for describing material sensorial qualities is only half the story, however. The other half is for designers to be articulate in making connections between material sensorial qualities and the expressivity that those material qualities can bring to a product; this is a much tougher task, for which new materials selection tools (see Section New materials selection tools) can be of assistance.

Samples and product exemplars

Our material judgments are continually renewed through sensory experiences arising from acquaintance with new or newly applied materials. Materials can surprise us with their properties once we are drawn-in and engaged with them beyond just visual appreciation. Thus, what we see, touch, handle, and hear—and under certain circumstances also smell and taste—greatly influences our thoughts about that material. Multisensoriality is a critical matter for user-centered materials selection. This third theme outlines an imperative to use material and product samples to generate *knowledge* about materials, to instill *values* about when to use or when to avoid a certain material, and to develop *skills* in linking sensorial qualities as codified on paper with the tangible experiences that come from first-hand acquaintance. Designers learn to "trust" materials through experiencing materials firsthand. Material samples allow easy cross-comparison of sensorial information, whereas product samples go a stage further to connect material properties and manufacturing processes within a realized form. Most usually, access to samples and product exemplars is achieved through some kind of materials library or collection, which may range from highly organized to highly eclectic, depending on its role to inspire and/or inform. Essentially, by making use of samples and product exemplars, designers are assisted in a transition from having *materials knowledge* to having *materials experience*.

Contextual considerations

Awareness of wider contextual matters that influence materials selection, to avoid self-centered or ill-informed materials decisions, is the fourth theme raised across the special dossier articles. Examples include proper consideration of the influences of stakeholders (e.g., clients and manufacturers) on materials selection activities, alongside more thorough understanding of how user attributes (e.g., gender, age, culture, and experience) affect material evaluations. These issues echo the general direction within user–product interaction studies to better understand how external factors modulate not only designers' decisions for the specification of a new product but also ultimately the ways in which users experience those products.

New materials selection tools

The fifth and final theme raised in the special dossier was the development of new materials selection tools operating on the basis of product experience criteria. The challenge here is to transform user-centered materials selection from an *intuitive* and ad hoc process to one that is structured, careful about its data set, and reliant on *evidence*. For example, if designers are ignorant about how materials influence people's product experiences and have no access to related user studies data, it cannot be possible to progress beyond the limits of personal experiences and gut reaction decision making (Karana, 2010). Thus, in recent years, independent efforts have been made by researchers distributed around the world to try to transform the "art" activities of materials selection closer to a "science" (to revisit the terminology of Ashby and Johnson, 2002). The most important factor driving this work has been a desire to provide designers with an evidence base arising from user studies, from which they can design for material *expression* and *experiences* beyond their own intuitions and idiosyncratic methods.

FOUR PROTOTYPICAL APPROACHES

Industrial design has evolved dramatically from its roots in product styling and beautification, into the professional practice of designing industrially produced artifacts, services, and systems for which the satisfaction of user needs and delivery of remarkable experiences is the central concern. In recent years, industrial design has become a more research-oriented profession, requiring analytical skills to complement the elevated levels of imagination and creativity that are considered prerequisites for design practice. Decision making based on fieldwork, user studies, and other empirically derived evidence is normal. Sometimes, designers are involved in generating that data themselves. Ethnographic studies, product benchmarking, and experience prototyping of concepts and interactions are now common tools and activities within the industrial designer's "product experience toolkit". However, what we have yet to see is the uptake of materials selection tools for product experience, built on data from user studies. The reason is simple: the work in this area is still largely experimental and has not yet reached commercial distribution.

In this section, four prototypical approaches to user-centered materials selection are introduced, taken from the work of the special dossier contributors. They represent ground-breaking thinking on how to support designers in undertaking user-centered materials decisions. They show the implementation of both software and physical tools, and offer glimpses of the probable directions that commercial tools will eventually take.

Ilse Van Kesteren: material perception tools

Following the findings of her research into how designers consider user–material interaction as an aspect of their product design process, Van Kesteren (2010, 2008) devised and trialed four materials selection tools ("questions tool", "pictures tool", "samples tool" and "relations tool"). Each of these tools had the aim of improving designers' materials selection activities in circumstances where designing for materials perception and user appreciation are critical. The tools are intended for use during the early phases of a design project as a discussion and inspiration source. Figure 24.2 shows the pictures tool (a set of cards with product images and sensorial information that can suggest a stated personality) and the samples tool (a set of physical material samples across material families, used to experience sensorial materials information firsthand). It is acknowledged that translating a sensorial-based material profile to engineering material properties and final materials selection is not easy; to this end, the relations tool provides a portfolio of look up tables linking sensorial qualities to material properties.

FIGURE 24.2

Pictures tool and samples tool for user-centered materials selection. © *2013 Ilse van Kesteren.*

Elvin Karana: meanings of materials tool

Karana's "Meanings of Materials tool" (2010, 2009) aimed to translate the main findings of her research into the meanings that people attribute to product materials into a tool to assist meaning-driven materials selection. The tool is promoted as a software assistant to gain materials inspiration for product design (Figure 24.3). It is particularly targeted at circumstances where intangible material

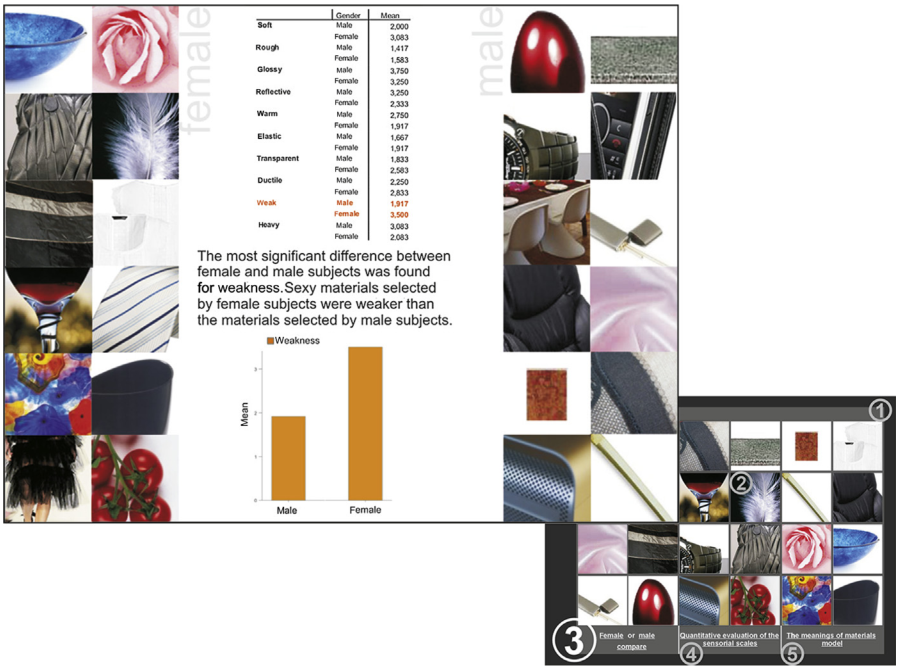

FIGURE 24.3

Meanings of materials tool: screen shots of gender-based analysis related to the material label "sexy". © *2013 Elvin Karana.*

"properties" need to be scrutinized. For example, the labels that people attach to materials (e.g., "sexy" and "cosy") can be cross-examined against sensorial information that significantly affects that labeling (e.g., hardness and transparency). The tool encourages designers to search for their own "meaning-evoking patterns" within the dataset; Karana does not have the intention to provide, nor does she consider it realistic to propose, simple causative or one-to-one relations between certain materials and certain meanings.

Hengfeng Zuo: material-aesthetics database

The "Material-Aesthetics Database" (2013; Figure 24.4) developed by Zuo (2003, 2010) is used to guide designers making materials selection based on tactile properties and perceived user experiences. Sensorial material information such as "perceived smoothness" and "perceived hardness" are linked in a database with design descriptors such as "comfortable", "safe", "modern" and "cheerful feeling".

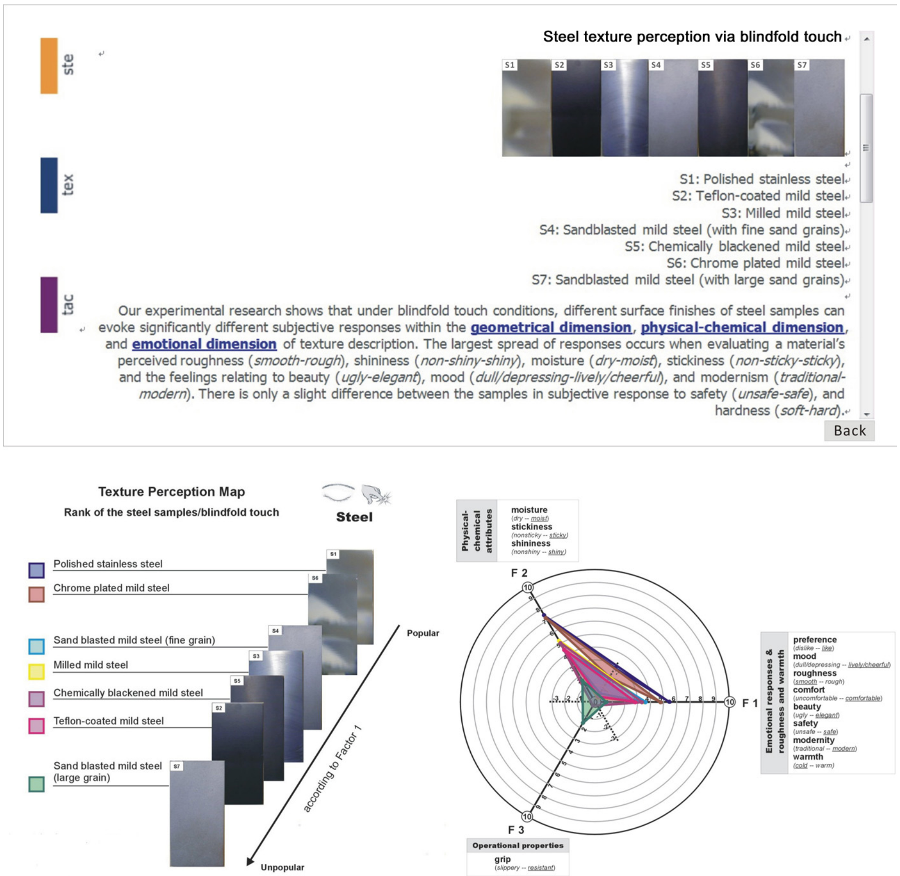

FIGURE 24.4

Material-aesthetics database: datasheets of tactual texture perception of steel samples (coded as "tac-tex-ste"). © *2013 Hengfeng Zuo.*

Therefore, the database can be consulted to determine what kind of texture to apply to preselected materials, based on research into people's tactile preferences for those materials under visual-touch and blindfold-touch conditions. Additionally, the database can give material suggestions based on achieving a desired tactile effect. Designers can consult texture perception maps within the database, which contain metrics on how individual materials/textures score against specific design criteria. Zuo recommends that the Material-Aesthetics database is used after initial functional screening of materials based on multiple criteria, for example, using the Cambridge Engineering Selector. The main difference between Karana's Meanings of Materials tool and Zuo's Material-Aesthetics database is the greater concentration on user tests of material surfaces in the latter, and people's perceptual frameworks for materials evaluation in the former.

Valentina Rognoli: expressive-sensorial atlas

Rognoli's "Expressive-Sensorial Atlas of Design Materials" (2010, 2004; Figure 24.5) was developed as a tool for deepening designers' knowledge and appreciation of material sensorial information and its effect on people's aesthetic and perceptive values. The atlas is provided as a portfolio of laminated A3 sheets containing various contents that encourage the development of an expressive-sensorial dialogue around materials. For example, material samples are included on many of the sheets to allow direct appraisal of tactile and visual properties, while accompanying text explains the variety of values

FIGURE 24.5

Expressive-sensorial atlas of design materials. © *2013 Valentina Rognoli.*

obtainable for the introduced material properties. Some of the sheets are designated as sensorial "maps", requiring designers to interact with a set of eight uniformly dimensioned material samples (poly(methyl methacrylate), polytetrafluoroethylene, glass, stainless steel, titanium, aluminum, copper, and lead) and place them in a rank order of property values, such as density or hardness. In this way, the atlas achieves experiential learning of material properties.

DISCUSSION

What lessons can we take from all the points raised so far? First, we see that the developers of new materials selection tools for product experience have not researched materials as such, but rather *people* and *their relationships with materials*. They present the results of rigorous enquiry into a humanistic angle on materials selection. Thus, the prototypical approaches outlined in the previous section stand at an interface between physical sciences (material as matter), psychology and physiology (materials as personal experiences), and social sciences (materials as collective experiences and cultural phenomena).

Second, if we take an interactional view of user—material—product relationships, then the starting point for product experiences is the sensorial information that emanates from a product (or more specifically for us, from the materials of that product). In everyday acquaintances, we experience materials based on the sense data that we detect from them, spanning visual, tactile, kinaesthetic, acoustic, olfactory, and gustatory modalities. Visual appraisals of materials have been dominant in literature, helping to strengthen our understanding of the role of materials in visual product perception, but we have seen in two of the prototypical approaches outlined in this chapter complementary research into experiences attributed to tactile material properties (Rognoli, 2010; Zuo, 2010). Other contributors to this book are currently working in the area of olfactory and gustatory material properties.

Third, we need ways to integrate sensorial materials information into the broader task of materials selection. A useful starting point might be to integrate the Kansei engineering approach to product development (Nagamachi, 1995). The basic approach with Kansei is to establish a relationship between the *perceptions* or *experiences* of users (e.g., impressions, feelings, meanings, associations, and emotions) and the various *attributes of a product* (which for our purposes we may limit to sensorial material information) that can affect those perceptions and experiences (Schütte et al., 2008). Kansei identifies product attributes by deconstructing products into "perceptual design elements" (Bouchard et al., 2003), each of which transmit certain sensorial information or sensory data, and which in turn affects user experience.

Finally, we must elevate the role of material and product samples—as well as appraisals of the materials of everyday things—to help foster a mind-set on materials selection that is critical about sensorial properties and people's reactions to them. Conversely, we should avoid materials selection processes that are entirely computer or paper based.

Perhaps the most fundamental point is that for user-centered materials selection, designers need a strong grounding in the *tangibility of materials* (e.g., strength, friction, and transparency) for materializing their designs, as witnessed, for example, through physical samples at material libraries, but

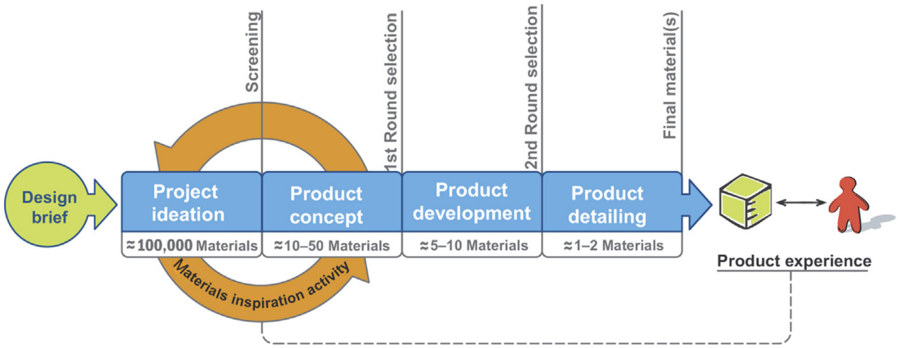

FIGURE 24.6
Positioning of materials inspiration activity relative to generic product design phases; data on approximate material choice reduction are taken from Ashby and Johnson (2002). *© 2013 Owain Pedgley.*

equally they need a strong comprehension of the *intangibility of materials* (e.g., meanings, labels, and emotions), as manifest through people's appraisals and experiences of product materials. Articulation of the connections between tangibility and intangibility will likely become a specialist area of materials knowledge for industrial design.

CONCLUSIONS

This chapter has introduced the idea of materials selection for product experience: what it involves, what knowledge it operates from, and how we may nurture expertise in the field. Such theoretical underpinning is seen as critical for intellectual and practical growth in the area, and especially relevant to the material needs of industrial designers.

One of the essential points raised throughout the chapter is that materials are admired, handled, evaluated, and otherwise experienced as an inevitable element of a physical artifact. However, elaboration of the experiential perspective on user—material—product relations has remarkably come to the fore only in recent years, with only a handful of specialist materials selection tools having been developed to assist in selection decisions for product experience. Nevertheless, the presence of four independently developed prototypical approaches to user-centered materials selection, outlined in this chapter, gives confidence that the area has potential to mature.

The most profound conclusion that can be drawn from the issues raised is that if industrial designers are to successfully achieve materials selection for product experience, it may be prudent for them to *avoid* a classic materials selection process, at least initially. That is, to avoid a hierarchical progression from the general (e.g., plastics) through the specific (e.g., polycarbonate) to the trade-named (e.g., Lexan 104). Why make such a proposition? Part of the remit of industrial design is to open doors, to play with the unusual and untested. This is not for some aimless experimentation, but to serendipitously hit upon a feasible material family or more specific material (and by implication finishes and shaping processes) that might just revolutionize a product sector or at very least provide an exciting new opportunity to differentiate a product from its competitors. So, rather than undertake an impersonal *materials selection process*, the industrial designer might be better encouraged to activate a personal *materials inspiration activity*, a conscious and subconscious hunt through existing materials—common and unusual—to help set material and product design directions that can meet defined user experience goals. “Materials selection” implies much design thinking has already occurred prior to engaging with materials decisions, rather like a realization route for a worked-out plan. Not as rash as an afterthought, but nevertheless some way distant from project ideation. In contrast, “materials inspiration” implies material thoughts that occur synchronously with design ideation and which to some extent permit the material to “lead the way” with regard to form- giving and possible user experiences.

To shift from materials selection to materials inspiration, it is necessary to augment the established flow of materials selection activities in product design. Figure 24.6 illustrates this, showing a new cyclic activity bridging project ideation and product conceptualization at the fuzzy front end of design. The consideration of materials at this stage is proposed to be playful rather than deductive, in so far as it harnesses designers’ creativity to consider ways in which a variety of material families, as well as specific materials, might leverage design ideas that can deliver intended user experiences. Such a materials inspiration activity would be an appropriate starting point for industrial designers’ contributions to material decisions.

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Interview with
Can Yalman

WHAT ARE THE KEY ASPECTS AFFECTING YOUR MATERIAL CHOICES?

We are a small design firm working within very different sectors, from tabletop goods, through furniture, to yacht design. We learn about materials from each sector, which I think is very important to the success of our business. Across these sectors, there is quite a wide variety of materials to choose from: ceramics, metals, rubbers, woods, fibres. There's a whole world of material possibilities out there. I think if you keep doing the same thing, eventually you will limit yourself to a certain type of material. So it's important to approach materials without prejudice. That is, to question what is believed to be true or right. With materials, we can think like a child. Anything can be anything for a child. Often it comes down to the will of a company to be able to produce in an innovative material. Of course, most of the time you have to follow within the production capabilities of the company you are working for, and what they have available to you. But you can also push the boundaries of production and use that side of materials.

ARE ANY OF THESE ASPECTS DIFFERENT THAN 10–20 YEARS BACK?

The range of available materials has definitely increased, because people are creating cycles of newer materials and new materials technologies. But more than that, I think because of the Internet our knowledge of different materials has increased. You hear about new developments quickly, and can assess whether they are applicable to your projects equally and quickly. That's been a big gain. Another aspect is that design is becoming a more specialized field. Before, a designer did almost all the work: research, design, form giving, choosing a material, and engineering the product. Today, with increased complexity and knowledge, we are approaching an era where we need specialists to help choose the right materials, or even to develop new materials for specific product applications.

IF WE SAY 'MATERIALS & SUSTAINABILITY', ... ?

I have mixed feelings about this. Yes, sustainability is very important. But endurance is also very important. Just because something is recycled or recyclable or is regenerated, doesn't automatically make it a better product. Quality is even more important than sustainability, because today many products are not just designed – they are *marketed* – for consumption. Reaching an emotional durability is very important: something that you will cherish and maybe pass on to the next generation. But at the same time, you need to have high quality material to last for that duration. For me, sustainability is in using natural materials as much as possible, and materials that are easily replenished: woods, metals, natural stones, marble. These types of materials have a certain perceived quality in them. When you look at products you consider antique today, one quality is that they all have a material that has lasted well, and often gotten better with age. So I think that's a very good point when choosing materials: what will happen to that product in 100 years? Will you want to keep it? When the

BIOGRAPHY

After graduating from Parsons School of Design NY with a Bachelor of Fine Arts in Product and Furniture Design, Can Yalman returned to Turkey. He worked at Arcelik / Beko for seven years as a staff and senior designer and in 2002 he started his own design studio, Can Yalman Design, where he and his team provide design services from concept creation to product development and manufacturing services. He believes good design should combine innovative design and practical solution solving while satisfying the needs of the user, manufacturer and the environment.

Image Credit: © CanYalmanDesign

system is geared towards consumerism, it's ridiculous to be talking about sustainability. I think we should be making products that last a long time. But then we can't build companies that last a long time because companies make money based on selling more products.

WHAT ABOUT 'MATERIALS & TECHNOLOGY' ...?

In Turkey, it's not always easy to access new materials technology, but we try to follow and use innovative materials as much as possible, like the use of carbon fibre in the 'Hexa' table for Nurus. I think smart materials will gain increasing importance, such as paints and surfaces that clean themselves, especially for ceramics. I think we'll be adapting a lot more materials found in nature, too. One other thing that can be interesting for the future is the realization of more and more handcrafts or hand processes as automated industrial scale processes. For instance, right now there's no such automatic system for making carbon fibre furniture. However, we have seen such technological progression already for glass and ceramics products. I think there will also be a need for more lightweight and stronger materials that push current boundaries, because energy consumption will need to be more efficient: lighter cars, lighter planes, lighter products. Production technology has also improved so much. With 3D printers, you can get a product very easily from the screen to the physical world. Currently the materials are limited, but it will improve. You may be able to do 3D printing in the final product materials — metals, ceramics and so forth. This will be very interesting.

MATERIALS & USER INTERACTION...?

People's first reaction to a product is through materials, or what their perception of the material is. A product has an air — an aura — that is put out through its material. Today, we have a lot of materials that look like something, but they're actually constructed from an entirely different material. For example, we have ceramics or tiles now that mimic wood to the last minute detail of the grain, the texture and soft touch. Your first reaction is that it's a wood covering, which of course is playful but misleading. The personality of a product is the collection of all the senses that you feel and that you interact with, from that product. Materials are a big part of this. It includes the first visual sense of form: the way light hits the surface, the shadows that are created, the way it reflects its surroundings, the hardness or softness of the finish. Then, when you touch it, how it feels; the way it smells, the way it sounds, and its weight. A lot of people's perception is that a heavy product is a high quality product, which is totally the opposite for carbon fibre. When we choose materials, we have to try to break down some of the old habits and material perceptions that people have. With certain products, people like to be surprised. So, user interaction requires an understanding of the consumer. Do you know what they want? Are you giving them what they want? Do they want something that is very light and innovative and expensive? I think these are the kinds of questions we need to push for materials selection, and that we already pose everyday for more general design decisions.

FROM WHERE DO YOU GET INSPIRATION AND INFORMATION FOR YOUR MATERIAL CHOICES?

It's very enlightening to see the manufacturing of different types of materials. Also, we get inspiration from nature, for product form or structural purposes. In the 'Hexa' table for Nurus, for example, we took inspiration from carbon nanotubes, the strongest building blocks found on Earth. For materials information, in recent years some very good material selection books have been published. Also we use Material ConneXion, which is an incredible library of materials where you can find something to your liking. Looking back to my work at Arcelik, we had projects where we made collaboration with other firms. For the 'Orbital' series of refrigerators, we collaborated with GE Plastics and Owens-Corning to make a shift from metal to plastic refrigerator doors. It was an R&D project to see the material potentials, but in the end we had a polycarbonate door that was easily mouldable, much less labour intensive to produce, and a lot lower cost. This is a product that has lasted twelve years in the marketplace, which is remarkable considering the material is plastic.

HOW DO YOU THINK MATERIALS SHOULD BE TAUGHT IN DESIGN EDUCATION?

The design education I got through Parsons was amazing because it really allowed me to get the concept of what design is, and where it should be going. Many of the questions that we are faced with today, such as 'should this product exist?', 'is this really the right product?', and 'is this sustainable?' were given to me back in the early 1990s through our teachers. So, I grew up with that design philosophy. Taking that forward for seven years at Arcelik was a rich learning experience. Especially working within teams and creating the right solutions to many of the firm's design problems was very influential in being able to work in the many different sectors that we do today. I don't think it is possible to design without giving proper regard to materials. From an engineering perspective, there is a set of rules. I mean, for a kettle for example, it needs to withstand a certain degree of heat, so you ask 'what are the material choices for that?' But when you approach product design like that, it's very difficult to innovate. In contrast, if you take a hands-on approach and personally experience a wide variety of materials, you can come across an opportunity where things connect and an appropriate new material can be found. So materials and design education needs to evolve. Design is a very tactile business. Products are very tactile. You can't get a sense of a product when you buy online. You can't even get a sense of the quality of the materials used. The same thing is true for design. Looking through a computer screen, it's very difficult to get the sense of materials. I think all design schools should have a library of materials, and also perhaps materials consultants who come in and work on certain projects.

Hexa Table

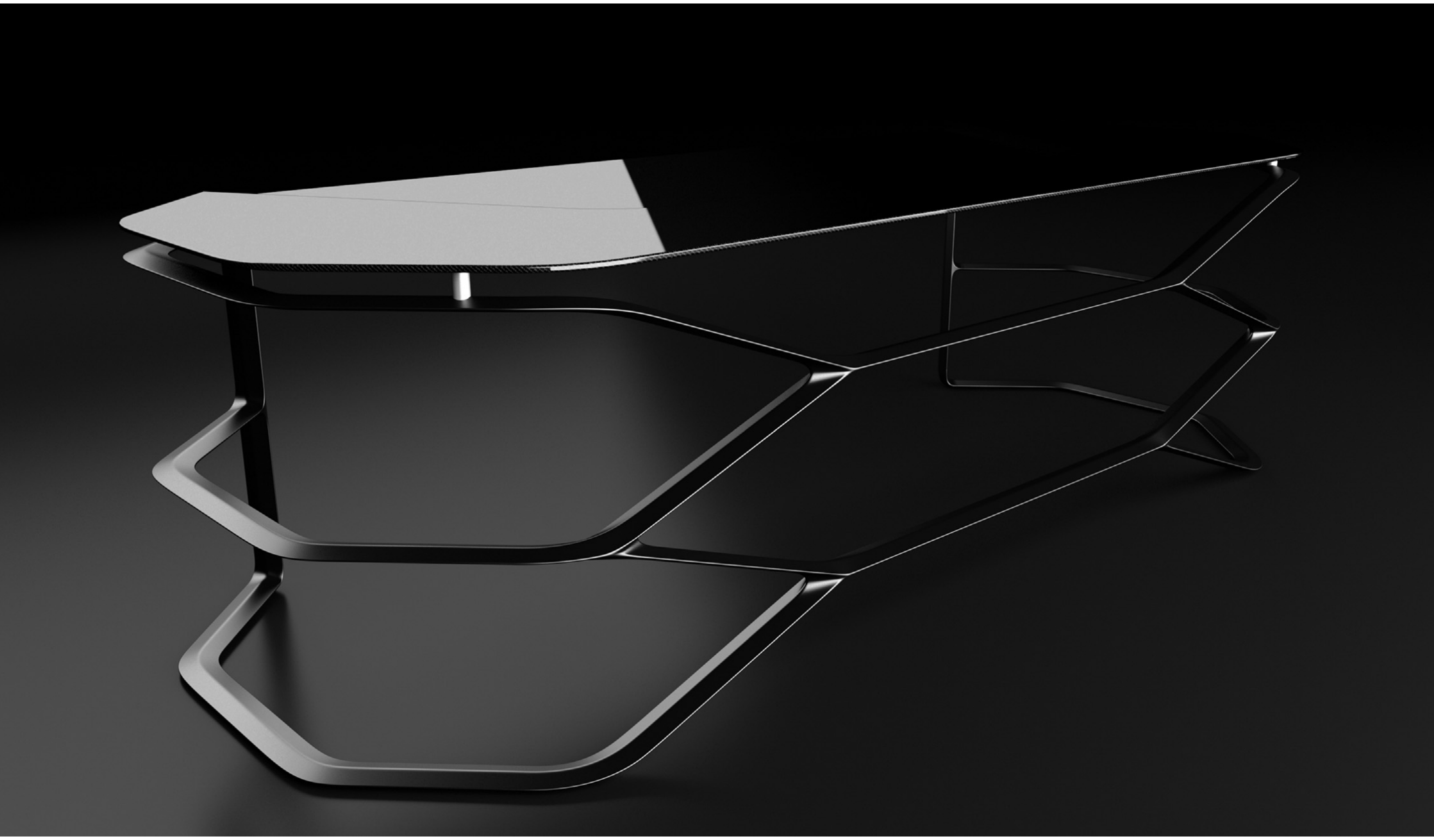
Client: Nurus

Year: 2009

Product Material(s): Carbon fiber and Aluminum

Brief Description: The idea of combining a super-light material with a super-strong structure is the originating point of Hexa. The hexagon table takes its inspiration from a carbon nanotube, which is ideally thought as a hexagonal network of carbon atoms that have been rolled into a seamless cylinder form. The amazing properties of this nanotube make it the strongest and stiffest material found on Earth. This sculptural desk is made of hand laid latticework of carbon fiber weaves combined with airplane grade aluminum, creating furniture for the office of the future.

Image Credit: © CanYalmanDesign



Mienterra Rug

Client: Step

Year: 2008

Product Material(s): Wool, Linen, Synthetic fibers

Brief Description: Mienterra employs a highly technical process that creates a unique multi dimensional rug. Here the manufacturing process itself is stepping in front of the material choices. Patented variable surface technology is used to weave a layered 3D surface.

Image Credit: © StepEvi

Orientile & Reptile Wall Tiles

Client: Kale

Year: 2006

Product Material(s): Ceramic

Brief Description: Ceramic is one of nature's most abundant and global materials: a natural resource that is easy to mould and manufacture. Its strengths in water resistance and surface durability make it an ideal choice for use in wall tiles, especially in wet areas. We prepared matte and glossy variations for the Reptile and Orientile products, to give a variety of finishing choices for the end user.

Image Credit: © Canakkale Seramik

Shah Cutlery Set

Client: Hisar

Year: 2004

Product Material(s): Stainless steel

Brief Description: The stainless steel used in this product is extremely hygienic, strong and durable. Quality stainless steel allows the cutlery to be used without problems for many years. In terms of sustainability, this puts the product in the most durable category. Simply by polishing, the cutlery can be restored back to its initial shine and grandeur. The material gives off a high shine, which allows for forms that create maximum reflection with simple molding procedures.

Image Credit: © Hisar

Interview with

Dick Powell

WHAT ARE THE KEY ASPECTS AFFECTING YOUR MATERIAL CHOICES?

When designing, you don't work on a concept in isolation of what it's going to be made of. You've always got that in the back of your mind, driven by both the functional and technical requirements of the product. The product sector is an important aspect. Clearly, if you're designing a digger then you have a different range of materials that you will be working with than if you're designing a mobile phone.

ARE ANY OF THESE ASPECTS DIFFERENT THAN 10–20 YEARS BACK?

Most of the things we do are plastic injection moulded, die cast metal or sheet metal bashed. There haven't been that many fundamental changes in the materials of products or the way things are made in the last two decades. However, a noticeable factor is that design for manufacture goes where the factories go. Nowadays, the factories are predominantly in Asia. In the UK we hardly have them anymore. One aspect of product design and manufacture that I can see growing and becoming more effective is product customization. People are willing to pay more for something special that they want to buy and own. Until now, what we have found is that the idea of customization is very seductive, but in practice, people aren't really bothered unless it's a very premium product that is involved. But also, people are not that good at it. Without some kind of caution and limitation to acceptable customization combinations, there is a danger of a product brand being compromised.

IF WE SAY 'MATERIALS & SUSTAINABILITY', ... ?

Sustainability is the new obligation in business. It is rapidly becoming a more and more important driver in what we do. It's higher and higher up the brief. Businesses have been taking it seriously for a few years, but at the level of manufacture, supply chain and carbon footprint. The really big step forward will come from consideration of the sustainability of the product itself, up front. We are going to be approaching a tipping point in this regard, where consumers start to demand more 'sustainable' products. When they start to demand them, then it becomes a commercial advantage to do better at attending to sustainability issues than your competitors. Some of the manufacturers whose brands are built around green credentials are already thinking about that.

The sustainability agenda is most evident in fast moving consumer goods, where disposal is the accepted outcome at the end of product life. Disassembly is important there – you tend not to do multiple shot mouldings that can't then be recycled as a result of the manufacturing process. Also there is avoidance of laminating different materials together.
On a broader perspective, I foresee a future involving the regeneration of a repair culture.

BIOGRAPHY

Dick is co-founder of design and innovation company Seymourpowell. He is Chairman of D&AD and has twice been President of D&AD. Dick has appeared on radio and television alongside co-founder Richard Seymour and has sat on the boards of the Design Council, the Design Business Association and the D&AD Executive. He was global design advisor to Samsung Electronics and is a member of the International Advisory Panel for Design in Singapore.

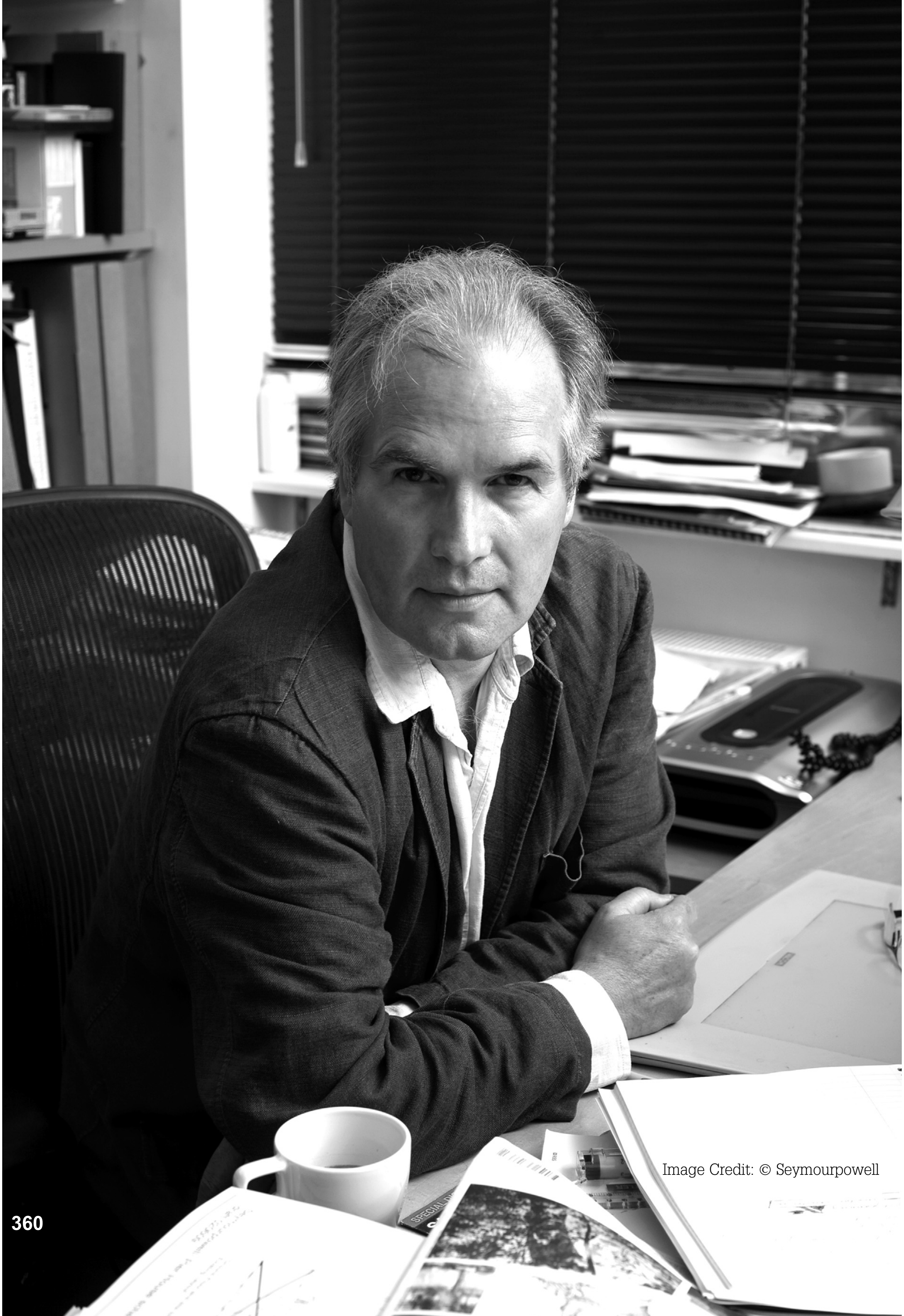


Image Credit: © Seymourpowell

For example, the European Commission may legislate for a product guarantee to be ten years. That puts a different perspective on how you build a product, and from what materials. If you design and make a product to be more durable to last ten years, it will inevitably cost more money. But if someone is paying more money for something then they're also less inclined to throw it away at the end of its life. That will have a big effect on the kinds of materials that we choose because we will need to use materials that are more robust, that last longer, that don't deteriorate at the same rate, and so on. A good example is the Dualit toaster — you send it back, and the firm will put a new element in it. But I can foresee a time when that might become a job for the rejuvenated repair corner shop: you take your toaster in, they'll get the elements ordered, assemble them for you, and give your fully functioning toaster back to you. We're looking forward to that day.

WHAT ABOUT 'MATERIALS & TECHNOLOGY' ...?

The whole area of smart materials is absolutely fascinating. They offer tremendous opportunities and will find a home in new products. Currently, we know *about* smart materials, but we rarely have the opportunity to use them. Other noticeable material technologies relate to product manufacture. There are some beautiful rapid prototyped products that you can buy, which couldn't be made any other way. The idea of manufacturing at home though — the dream that anyone can just press a button and create, for example, a new washing up bowl when they feel like it — personally I think is still a long way off. The advantages have to really outweigh the disadvantages. It's probably so much unnecessary effort compared with taking a trip to the shops and buying a new washing up bowl. So that's going to take some time to happen. And then the real truth of it all — which is going to take even more solving — is that the great majority of products are not a single material. They are mechanical, they have metal parts, electronic parts, digital parts, and electrical parts: all those materials come together in a product. Capability to rapid prototype that diversity of components in a home environment will not come for many years.

MATERIALS & USER INTERACTION...?

Materials are very important in that they establish a perception of a product very quickly. People recognize what a material is before they even touch it or hold it, so there's an immediate visual aspect to your choice of materials. And immediately after that, as soon as you start handling something, you get a secondary tactile view of what the material is. It's important to select materials that are not only great to use but also to feel. Emotions and reactions from materials really condition your appraisal of the quality of a product — for example, how expensive it is, how easy it is to use and hold, and so forth. Having materials that genuinely form part of the interaction with a product or service really conjures tremendous opportunities. So the interaction is not just through displays, but in the way you touch and hold things. For example, the use of materials which when gripped swell and form to an individual's hand.

FROM WHERE DO YOU GET INSPIRATION AND INFORMATION FOR YOUR MATERIAL CHOICES?

The basic rule of thumb is you have to keep your eyes open all the time. I think a designer is a radar scanner, where he or she is looking at, observing and accumulating information and knowledge. However, if you're only looking — as opposed to seeing — you're never going to accumulate that massive amount of information from which intuition is born. Intuition is a bit like an iceberg: the tip that projects into your consciousness is there because of a huge amount of cognitive stuff that's being going on in your brain for ages. If you're not seeing things, you're never replenishing that pool of knowledge. Good designers see things in other industries, they see things in other sectors, or they'll see a material or a finish or a particular look on something else and say, 'that's interesting' and mentally log it away, eventually to resurface during a design project. If we talk about information sources, I think manufacturers who have new materials need to be more creative about how they let designers and manufacturers know about them.

HOW DO YOU THINK MATERIALS SHOULD BE TAUGHT IN DESIGN EDUCATION?

I find that graduates are very poorly informed generally — far less informed than they need to be. The number one priority would be to have a complete understanding of the structural qualities of materials, and how to design to extract their potential and minimize material consumption. The second priority would be the processes by which we deliver those things; the ways in which we can transform materials into products. The third priority would be some sort of mechanism to keep students' eyes open. Clearly a design department in a university needs to have a stock of magazines, journals and URLs where students can go to keep informed about what is happening in the field of materials and design. It's also important to have access to material samples, and to get people making those materials to come in and talk about their potential and so on. In an educational context though, it's much better to have products than material samples. You've only got to look at a complex blow moulding sawn in half to see exactly what the material issues are and why it's made the way it is. And no amount of teaching will really compensate for that — you've just got to see it.

Dove Aerosol Petal Actuator

Client: Unilever

Year: 2007

Product Material(s): TPE (Thermoplastic Elastomers)

Brief Description: TPE, a rubber-like material, was used for the Dove Aerosol Petal Actuator to provide a soft touch and sensual experience. Dove is well known as a feminine brand and this was reflected through the design, concealing the actuator with the TPE material. Instead of pressing down on hard plastic, the woman using the deodorant can press lightly on a soft warm cover.

Image Credit: © Seymourpowell

Signal White Now Packaging

Client: Unilever

Year: 2008

Product Material(s): rPET (recycled polyethylene terephthalate)

Brief Description: The Signal White Now packaging was designed to amplify the new product — whitening toothpaste. The paste has a clear outer gel and a deep blue core, and the packaging echos this. The material rPet was chosen to enable the transparent carton to be 'crystal clear' and glossy to reveal the deep blue colored tube inside. It also had to be resistant to scratches and run down existing high speed, automated assembly production lines.

Image Credit: © Seymourpowell

Liquavista Mobile Telephone Concept

Client: Liquavista

Year: 2008

Product Material(s): Electrowetting

Brief Description: Electrowetting involves modifying the surface tensions of liquids using a voltage. The voltage causes the surface to become increasingly hydrophilic (wettable). Through this process, Seymourpowell created a watch featuring a full color, highly legible display, replacing the traditional black on gray LCD. They also created a mobile phone concept which transforms the back of a phone into a dynamic graphic display triggered when the phone is used.

Image Credit: © Seymourpowell

Quantum Saddle

Client: Quantum

Year: 2009

Product Material(s): Carbon fiber, aluminum, leather, various densities of foam

Brief Description: The main material used in the Quantum saddle was carbon fiber because of its ability to be both lightweight, but extremely strong. Its use was a breakthrough in the construction of traditional saddles as designers were able to achieve a contoured fit to the horse's back. Intensive research demonstrated the saddle evenly distributes pressure over the horse's back and away from its shoulders. The saddle is covered in high quality leather providing a very traditional look to the structure.

Image Credit: © Seymourpowell

Inspirational Resources for Materials and Design

Lists of inspirational and informative resources for design can never be exhaustive, but they do provide a good starting point to navigate the huge pool of information accessible to designers. The entries listed here are either some of the most established resources of their type, or personal favorites of the Editors. We present them to provide a head start for anyone seeking inspiration for their materials and design work. All of the listed resources have a Web presence.

PHYSICAL SAMPLE COLLECTIONS

The number of material libraries or physical sample collections has grown considerably since the turn of the century. Their basic principle is to allow visitors to appraise materials hands-on, thereby progressing beyond information gained solely from photographs and data sheets. Collections can be sorted into three broad categories: those hosted by educational institutions, those run by organizations or associations, and those operating as part of a commercial consultancy service. Please note that these collections are rarely open to the public and most do not provide open access. It is therefore vital to check if an appointment is needed before visiting.

Educational Institutions

California College of The Arts – 'New Materials Library' (USA)
http://libraries.cca.edu/new-materials-lib/
Camberwell College of Arts – 'Camberwell Material Library' (UK)
http://cltad.arts.ac.uk/groups/camberwellmateriallibrary/
College for Creative Studies – 'Colors and Material Library' (USA)
http://www.collegeforcreativestudies.edu/student-resources/student-services-and-resources/library/colors-materials-library/
Delft University of Technology – 'Made of..' (Netherlands)
http://www.io.tudelft.nl/madeof/
Harvard University Graduate School of Design – 'Materials Collection Frances Loeb Library' (USA)
http://www.gsd.harvard.edu/#/loeblibrary/collections/materials-collection/

Kingston University — 'Rematerialise Sustainable Materials Library' (UK)
http://extranet.kingston.ac.uk/rematerialise/
London Metropolitan University — 'Materials and Products Collection' (UK)
http://www.londonmet.ac.uk/services/sas/library-services/commercial/materials-products.cfm
Politecnico di Milano — 'Materiali e Design' (Italy)
http://www.politeca.polimi.it/
Politecnico di Torino — 'MATto' (Italy)
http://areeweb.polito.it/ricerca/MATto.it/
Rhode Island School of Design — 'Material Resource Center' (USA)
http://library.risd.edu/materialslibrary.html
Royal Danish Academy of Fine Arts — 'Material Collection' (Denmark)
http://www.karch.dk/uk/Menu/About+The+School/Facilities/Material+Collection/
Swiss Institutions and Universities — 'Material Archiv' (Switzerland)
http://www.materialarchiv.ch/cms/
The New England School of Arts and Design at Suffolk University — 'Materials & Resource Library' (USA)
http://www2.suffolk.edu/nesad/17940_18105.htm
University of Texas at Austin — 'Materials Lab' (USA)
http://soa.utexas.edu/matlab/
Virginia Commonwealth University in Qatar — 'Materials Library' (Qatar)
http://www.qatar.vcu.edu/library/use-the-libraries/materials-library/

Organizations

Materialbiblioteket (Sweden)
http://materialbiblioteket.se/showroom/
Materioteca (Italy)
http://www.materioteca.it/
Matrec (Italy)
http://www.matrec.it/it/chi-siamo/il-gruppo-matrec/
Institute of Making, University College London (UK)
http://www.instituteofmaking.org.uk/materials-library/
Science Museum London, Challenge of Materials (UK)
http://www.sciencemuseum.org.uk/visitmuseum/galleries/challenge_of_materials.aspx

Commercial Consultancies

Innovatheque (France)
http://www.innovatheque.fr/
MaTech (Italy)
http://www.matech.it/
Materfad (Spain)
http://es.materfad.com/

Materia (Netherlands)
http://www.materia-ic.com/
Material ConneXion (Worldwide)
http://materialconnexion.com/
Material Lab (UK)
http://www.material-lab.co.uk/
Materialsgate (Germany)
http://www.materialsgate.de/
Materials Monthly (USA)
http://www.papress.com/other/materialsmonthlyOLD/
MateriO (Europe)
http://www.materio.com/
Modulor (Germany)
http://www.modulor.de/
Raumprobe (Germany)
http://www.raumprobe.de/
SCIN (UK)
http://www.scin.co.uk/
Sensolab (France)
http://www.sensolab.fr/
Stylepark Material Works (Germany)
http://www.stylepark.com/en/material/

ONLINE RESOURCES

The Internet has become a vital hub in the communication of new and emerging materials for design. The breadth and depth of materials information available through the Internet is astounding. Here we present listings for information sites, blogs and material-related events that will be of special interest to designers.

Information Sites

2PSM Psychosensorial Properties	http://www.2psm.fr/
Archello	http://www.archello.com/en/materials/
Architronic Products & Materials	http://www.architonic.com/
Azom A-Z of Materials	http://www.azom.com/
Biopolymer.Net	http://www.biopolymer.net/
Design 4 Sustainability (Materials)	http://www.design-4-sustainability.com/materials/
Design Insite	http://www.designinsite.dk/
Ecolect	http://www.ecolect.net/
Haute Innovation	http://www.haute-innovation.com/

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IDSA Materials & Processes Section	http://www.idsa.org/sections/materials-and-processes/
Inventables	http://www.inventables.com/
Material Sense	http://www.materialsense.com/
Material Stories	http://materialstories.com/
Materials Café	http://www.materialscafe.de/
Matweb	http://www.matweb.com/
MTRL	http://www.mtrl.com/portal/site/mtrl/
Product by Process	http://bencollette.com/productbyprocess/
Selecting Materials	http://selectingmaterials.com/
Trans Studio	http://www.transstudio.com/
Transmaterial	http://transmaterial.net/

Blogs

Chris Lefteri Blog	http://blog.chrislefteri.com/
Core 77 Materials Blog	http://www.core77.com/blog/materials/
Hello Materials Blog	http://hellomaterialsblog.ddc.dk/

Events

Material Vision	http://material-vision.messefrankfurt.com/
Materialica	http://www.materialica.de/
Materials Education Symposia	http://www.materials-education.com/

Index

Note: Page numbers with "f" denote figures; "t" tables; "b" boxes.

D

E

F

G

H

I

J

K

L

M