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Preface

Ten years ago, when we first began treading in the murky waters of "smart" materials and micro-systems, we had little information to guide us. Although there had already been rapid expansion in these technologies in the science and engineering fields, particularly in regard to sensor development, their entry into the design arena was, at best, idiosyncratic. We found many novelty items and toys – mugs that changed color when hot coffee was poured inside, and rubber dinosaurs whose heads bobbed when connected to a battery – and we noted that many designers were beginning to incorporate the language of smart materials, albeit not the technologies themselves. There were proposals for buildings to be entirely sheathed with "smart" gel, or for "smart" rooms that would deform individually for each occupant according to their specific physiological and psychological needs. Precisely *how* this would happen remained mysterious, and it was often presumed that the magical abilities attributed to the smart designs were simply technicalities that someone else – an engineer perhaps – would figure out.

These proposals troubled us from two aspects. The first was clearly that designers were considering these very new and sophisticated materials and technologies to fit right into their normative practice, making design simpler as the manifestation of intentions could shift from the responsibility of the designer to the material itself. One would no longer have to carefully and tediously design wall articulation to create a particular visual effect, as the material would be capable of creating any effect, one only had to *name* it. In addition to this abdication of responsibility to an as-yet undefined technology, we were also concerned with the lack of interest in the actual *behavior* of the technology. By framing these technologies from within the design practice, architects and designers were missing the opportunity to exploit unprecedented properties and behaviors that should have been leading to radically different approaches for design rather than only to the manifestation of designs constrained by the hegemony of existing practice.

When we looked at the other end of the spectrum to examine what scientists and engineers were doing, however, we encountered equally problematic responses. Much of the early development had been geared toward miniaturization and/or simplification of existing technologies – using instantaneous labs on a chip to reduce the time of the unwieldy chromatography process; replacing complex mechanical valves with seamless shape memory actuators. As manufacturing processes were adapted to these specialized materials, and advances in imaging allowed fabrication at the nano scale level, the development shifted from problem solving to "technology push." Countless new materials and technologies emerged, many looking for a home, and a potential application.

We were confronted with trying to fit round pegs – highly specific technologies – into square holes – incredibly vague architectural aspirations. Neither end seemed appropriate. We did not have the kind of problems that a new technology could easily step in to solve, nor did we have any idea about just what kind of potential could be wrung from the behaviors of these technologies. We needed to bridge the very large gap between the owners of the relevant knowledge and the inventors of the potential applications.

This transfer of knowledge has not been easy. Scientific and engineering information typically enters the design realm already "dumbed down." Architects and designers don't need to know how something works, they just need to know the pragmatics – how big is it, what does it look like? This approach, unfortunately, keeps the design professions at arm's length, preventing not only the full exploitation of these technologies, but also denying a coherent vision of the future to help direct development in the science and engineering disciplines. Over the last ten years, we have struggled in our own research, and in our classes, to find the fluid medium between knowledge and application, so that both are served. This book represents the culmination of that decade of investigation and experimentation.

Our primary intention for the book's content was the development of a coherent structure and language to facilitate knowledge transfer at its highest level. There are certain phenomena and physical properties that must be fully understood in order to design a behavior. Fundamental for architects and designers is the understanding that we cannot frame these technologies within our own practice, we must instead inflect their deployment based on their inherent characteristics. For example, as evidenced by the continuing desire of architects to produce smart facades, we have a tendency to ask these technologies to act at our normative scale – the scale of a building. Most of these technologies, however, perform at the molecular and micro-scales. How differently might we think and design if we engaged these scale differences rather than ignoring them?

Clearly, the knowledge about these materials and technologies within the science and engineering realms is so vast that any given engineer will have a different knowledge set than another, even in the same area of specialty. What knowledge, then, should we bring across the divide to the designers? We identified some fundamental laws of physics and principles of materials science that we felt could serve as the building blocks to allow the derivation of behaviors most relevant to the design professions. Several different materials, components and assemblies were then chosen and described to illustrate how these building blocks could be applied to help understand and ultimately exploit each example's characteristics. We fully expect that the specific materials and technologies referred to in this book will soon become obsolete, but we strongly believe that the theoretical structure developed herein will transcend the specifics and be applicable to each new material that we may confront in the future.

Michelle Addington
Cambridge, Massachusetts

delimited by the material surface, instead it may be reconfigured as the *zone in which change occurs*. The image of the building boundary as the demarcation between two different environments defined as single states – a homogeneous interior and an ambient exterior – could possibly be replaced by the idea of multiple energy environments fluidly interacting with the moving body. Smart materials, with their transient behavior and ability to respond to energy stimuli, may eventually enable the selective creation and design of an individual's sensory experiences.

Are architects in a position or state of development to implement and exploit this alternative paradigm, or, at the very least, to rigorously explore it? At this point, the answer is most probably no, but there are seeds of opportunity from on-going physical research and glimpses of the future use of the technology from other design fields. Advances in physics have led to a new understanding of physical phenomena, advances in biology and neurology have led to new discoveries regarding the human sensory system. Furthermore, smart materials have been comprehensively experimented with and rapidly adopted in many other fields – finding their way into products and uses as diverse as toys and automotive components. Our charge is to examine the knowledge gained in other disciplines, but develop a framework for its application that is suited to the unique needs and possibilities of architecture.

1.4 Characteristics of smart materials and systems

DEFINITIONS

We have been liberally using the term 'smart materials' without precisely defining what we mean. Creating a precise definition, however, is surprisingly difficult. The term is already in wide use, but there is no general agreement about what it actually means. A quick review of the literature indicates that terms like 'smart' and 'intelligent' are used almost interchangeably by many in relation to materials and systems, while others draw sharp distinctions about which qualities or capabilities are implied. NASA defines smart materials as 'materials that "remember" configurations and can conform to them when given a specific stimulus',[3] a definition that clearly gives an indication as to how NASA intends to investigate and apply them. A more sweeping definition comes from the *Encyclopedia of Chemical Technology*: 'smart materials and structures are those objects that sense environmental events, process that sensory information, and then act on the environment'.[4] Even though these two definitions seem to be referring to the same type of behavior, they are poles apart. The first definition refers to materials as substances, and as such, we would think of elements, alloys or even compounds, but all would be identifiable and quantifiable by their molecular structure. The second definition refers to materials as a series of actions. Are they then composite as well as singular, or assemblies of many materials, or, even further removed from an identifiable molecular structure, an assembly of many systems?

If we step back and look at the words 'smart' and 'intelligent' by themselves we may find some cues to help us begin to conceptualize a working definition of 'smart materials' that would be relevant for designers. 'Smart' implies notions of an informed or knowledgeable response, with associated qualities of alertness and quickness. In common usage, there is also frequently an association with shrewdness, connoting an intuitive or intrinsic response. Intelligent is the ability to acquire knowledge, demonstrate good judgment and possess quickness in understanding.

Interestingly, these descriptions are fairly suggestive of the qualities of many of the smart materials that are of interest to us. Common uses of the term 'smart materials' do indeed suggest materials that have intrinsic or embedded quick response capabilities, and, while one would not commonly think about a material as shrewd, the implied notions of cleverness and discernment in response are not without interest. The idea of discernment, for example, leads one to thinking about the inherent power of using smart materials selectively and strategically. Indeed, this idea of a strategic use is quite new to architecture, as materials in our field are rarely thought of as performing in a direct or local role. Furthermore, selective use hints at a discrete response – a singular action but not necessarily a singular material. Underlying, then, the concept of the intelligent and designed response is a seamless quickness – immediate action for a specific and transient stimulus.

Does 'smartness', then, require special materials and advanced technologies? Most probably no, as there is nothing a smart material can do that a conventional system can't. A photochromic window that changes its transparency in relation to the amount of incident solar radiation could be replaced by a globe thermometer in a feedback control loop sending signals to a motor that through mechanical linkages repositions louvers on the surface of the glazing, thus changing the net transparency. Unwieldy, yes, but nevertheless feasible and possible to achieve with commonly used technology and materials. (Indeed, many buildings currently use such a system.) So perhaps the most unique aspects of these materials and technologies are the underlying concepts that can be gleaned from their behavior.

Whether a molecule, a material, a composite, an assembly, or a system, 'smart materials and technologies' will exhibit the following characteristics:

- Immediacy – they respond in real-time.
- Transiency – they respond to more than one environmental state.
- Self-actuation – intelligence is internal to rather than external to the 'material'.
- Selectivity – their response is discrete and predictable.
- Directness – the response is local to the 'activating' event.

It may be this last characteristic, directness, that poses the greatest challenge to architects. Our building systems are neither discrete nor direct. Something as apparently simple as changing the temperature in a room by a few degrees will set off a Rube Goldberg cascade of processes in the HVAC system, affecting the operation of equipment throughout the building. The concept of directness, however, goes beyond making the HVAC equipment more streamlined and local; we must also ask fundamental questions about the intended behavior of the system. The current focus on high-performance buildings is directed toward improving the operation and control of these systems. But why do we need these particular systems to begin with?

The majority of our building systems, whether HVAC, lighting, or structural, are designed to service the building and hence are often referred to as 'building services'. Excepting laboratories and industrial uses, though, buildings exist to serve their occupants. Only the human body requires management of its thermal environment, the building does not, yet we heat and cool the entire volume. The human eye perceives a tiny fraction of the light provided in a building, but lighting standards require constant light levels throughout the building. If we could begin to think of these environments at the small scale – what the body needs – and not at the large scale – the building space – we could dramatically reduce the energy and material investment of the large systems while providing better conditions for the human occupants. When these systems were conceived over a century ago, there was neither the technology nor the knowledge to address human needs in any manner other than through large indirect systems that provided homogeneous building conditions. The advent of smart materials now enables the design of direct and discrete environments for the body, but we have no road map for their application in this important arena.

1.5 Moving forward

Long considered as one of the roadblocks in the development and application of smart materials is the confusion over which discipline should 'own' and direct the research efforts as well as oversee applications and performance. Notwithstanding that the 'discovery' of smart materials is attributed to two chemists (Jacques and Pierre Curie no less!), the disciplines of mechanical engineering and electrical engineering currently split ownership. Mechanical engineers deal with energy stimuli, kinematic (active) behavior and material structure, whereas electrical engineers are responsible for microelectronics (a fundamental component of many smart systems and assemblies), and the operational platform (packaging and circuitry). Furthermore, electrical engineers have led the efforts toward miniaturization, and as such, much of the fabrication, which for most conventional materials would be housed in mechanical engineering, is instead under the umbrella of electrical engineering.

This alliance has been quite effective in the development of new technologies and materials, but has been less so in regard to determining the appropriate applications. As a result, the smart materials arena is often described as 'technology push' or, in other words, technologies looking for a problem. Although this is an issue that is often raised in overviews and discussions of smart materials, it has been somewhat nullified by the rapid evolution and turnover of technologies in general. Many industries routinely adopt and discard technologies as new products are being developed and old ones are upgraded. As soon as knowledge of a new smart material or technology enters the public realm, industries of all sizes and of all types will begin trying it out, eliminating the round pegs for the square holes. This trial and error of matching the technology to a problem may well open up unprecedented opportunities for application that would have gone undetected if the more normative 'problem first' developmental sequence had occurred. For architecture, however, this reversal is much more problematic.

In most fields, technologies undergo continuous cycles of evolution and obsolescence as the governing science matures;

as a result, new materials and technologies can be easily assimilated. In architecture, however, technologies have very long lifetimes, and many factors other than science determine their use and longevity. There is no mechanism by which new advances can be explored and tested, and the small profit margin in relation to the large capital investment of construction does not allow for in situ experimentation. Furthermore, buildings last for years – 30 on average – and many last for a century or more. In spite of new construction, the yearly turnover in the building stock is quite low. Anything new must be fully verified in some other industry before architects can pragmatically use it, and there must also be a match with a client who is willing to take the risk of investing in any technology that does not have a proven track record.

The adoption of smart materials poses yet another dilemma for the field of architecture. Whereas architects choose the materials for a building, engineers routinely select the technologies and design the systems. Smart materials are essentially material systems with embedded technological functions, many of which are quite sophisticated. Who, then, should make the decisions regarding their use? Compounding this dilemma are the technologies at the heart of smart materials; the branches of mechanical and electrical engineering responsible for overseeing this area have virtually no connection to or relationship with the engineering of building systems. Not only are smart materials a radical departure from the more normative materials in appearance, but their embedded technology has no precedent in the large integrated technological systems that are the standard in buildings.

How can architects and designers begin to explore and exploit these developing technologies and materials, with the recognition that their operating principles are among the most sophisticated of any technologies in use? Although architecture is inherently an interdisciplinary profession, its practice puts the architect at the center, as the director of the process and the key decision-maker. The disciplines that we must now reach out to, not only mechanical and electrical engineering, but also the biological sciences, have little common ground. There are no overlapping boundaries in knowledge, such as you might find between architecture and urban design, and there is no commonality of problem, such as you might find between architecture and ecology. Our knowledge base, our practice arena, and even our language are split from those in the smart materials domain. Ultimately, our use of these materials will put us into the heady role of manipulating the principles of physics.

1.6 Organization of the text

The objectives of this book are thus three-fold. The first is to provide a primer on smart materials, acquainting architects and designers with the fundamental features, properties, behaviors and uses of smart materials. Of particular importance is the development of a vocabulary and a descriptive language that will enable the architect to enter into the world of the material scientist and engineer. The second objective is the framing of these new materials and technologies as behaviors or actions and not simply as artifacts. We will be describing smart materials in relation to the stimulus fields that surround them. Rather than categorizing materials by application or appearance, we will then categorize them in relation to their actions and their energy stimulus. Our third objective is the development of a methodological approach for working with these materials and technologies. We will successively build systems and scenarios as the book progresses, demonstrating how properties, behaviors, materials and technologies can be combined to create new responses. If these three objectives are met, the designer will be able to take a more proactive stance in determining the types of materials and systems that should be developed and applied. Furthermore, competency in the foundations of energy and material composition behavior will eventually allow the architect or designer to think at a conceptual level 'above' that of the material or technology. One of the constants in the field of smart materials is that they are continuously being updated or replaced. If we understand classes of behaviors in relation to properties and energy fields, then we will be able to apply that understanding to any new material we may 'meet' in the future.

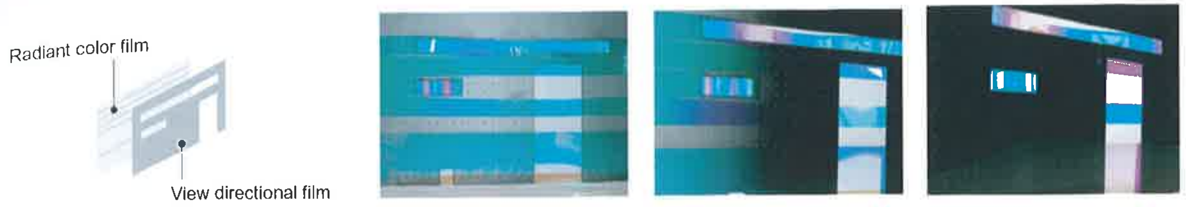
To pull these objectives together, the overall organization of the book follows a bipartite system; categories of behavior will be established and then will be overlaid with increasing component and system complexity. Chapter 2 serves as the entry into the subject of material properties and material behavior, whereas Chapter 3 first posits the framework through which we will categorize smart materials. We will establish a basic relationship between material properties, material states and energy that we can use to describe the interaction of all materials with the environments – thermal, luminous and acoustic – that surround the human body. This basic relationship forms a construct that allows us to understand the fundamental mechanisms of 'smartness'. The resulting construct will form the basis not only for the categories, but will also be useful as we discuss potential combinations and applications.

Smartness in a material or system is determined by one of two mechanisms, which can be applied directly to a singular material, and conceptually to a compound system (although individual components may well have one of the direct mechanisms). If the mechanism affects the internal energy of the material by altering either the material's molecular structure or microstructure then the input results in a property change of the material. (The term 'property' is important in the context of this discussion and will be elaborated upon later. Briefly, the properties of a material may be either intrinsic or extrinsic. Intrinsic properties are dependent on the internal structure and composition of the material. Many chemical, mechanical, electrical, magnetic and thermal properties of a material are normally intrinsic to it. Extrinsic properties are dependent on other factors. The color of a material, for example, is dependent on the nature of the external incident light as well as the micro-structure of the material exposed to the light.) If the mechanism changes the energy state of the material, but does not alter the material *per se*, then the input results in an exchange of energy from one form to another. A simple way of differentiating between the two mechanisms is that for the property change type (hereafter defined as Type I), the material absorbs the input energy and undergoes a change, whereas for the energy exchange type (Type II), the material stays the same but the energy undergoes a change. We consider both of these mechanisms to operate directly at the micro-scale, as none will affect anything larger than the molecule, and furthermore, many of the energy-exchanges take place at the atomic level. As such, we cannot 'see' this physical behavior at the scale at which it occurs.

▲ **Figure 1-5** Radiant color film. The color of the transmitted or reflected light depends upon the vantage point. Observers at different places would see different colors (*see* Chapter 6)

HIGH-PERFORMANCE VERSUS SMART MATERIALS

We will soon begin to use the construct just described to begin characterizing smart materials, and specifically look at materials that change their properties in response to varying external stimuli and those that provide energy transformation functions. This construct is specific to smart materials. It does not reflect, for example, many extremely exciting and useful new materials currently in vogue today. Many of these interesting materials, such as composites based on carbon fibers or some of the new radiant mirror films, change neither their properties nor provide energy transfer functions; and hence are not smart materials. Rather, they are what might best be described as 'high-performance' materials. They often have what might be called 'selected and designed properties' (e.g., extremely high strength or stiffness, or particular reflective properties). These particular properties have been optimized via the use of particular internal material structures or compositions. These optimized properties, however, are static. Nevertheless, we will still briefly cover selected high performance materials later in Chapter 4 because of the way they interact with more clearly defined smart materials.



▲ **Figure 1-6** Design experiment: view directional film and radiant color film have been used together in this façade study. (Nyriabu Nyriabu)

TYPE 1 MATERIALS

Based on the general approach described above, smart materials may be easily classified in two basic ways. In one construct we will be referring to materials that undergo changes in one or more of their properties – chemical, mechanical, electrical, magnetic or thermal – in direct response to a change in the external stimuli associated with the environment surrounding the material. Changes are direct and reversible – there is no need for an external control system to cause these changes to occur. A photochromic material, for example, changes its color in response to a change in the amount of ultraviolet radiation on its surface. We will be using the term 'Type 1' materials to distinguish this class of smart materials.

Chapter 4 will discuss these materials in detail. Briefly, some of the more common kinds of Type 1 materials include the following:

- Thermochromic – an input of thermal energy (heat) to the material alters its molecular structure. The new molecular structure has a different spectral reflectivity than does the original structure; as a result, the material's 'color' – its reflected radiation in the visible range of the electromagnetic spectrum – changes.
- Magnetorheological – the application of a magnetic field (or for electrorheological – an electrical field) causes a

change in micro-structural orientation, resulting in a change in viscosity of the fluid.

- Thermotropic – an input of thermal energy (or radiation for a phototropic, electricity for electrotropic and so on) to the material alters its micro-structure through a phase change. In a different phase, most materials demonstrate different properties, including conductivity, transmissivity, volumetric expansion, and solubility.
- Shape memory – an input of thermal energy (which can also be produced through resistance to an electrical current) alters the microstructure through a *crystalline* phase change. This change enables multiple shapes in relationship to the environmental stimulus.

▲ **Figure 1-7** A 'cloth' made by weaving fiber-optic strands that are lighted by light-emitting diodes (LEDs). (Yokiko Koide)

TYPE 2 MATERIALS

A second general class of smart materials is comprised of those that transform energy from one form to an output energy in another form, and again do so directly and reversibly. Thus, an electro-restrictive material transforms electrical energy into elastic (mechanical) energy which in turn results in a physical shape change. Changes are again direct and reversible. We will be calling these 'Type 2' materials. Among the materials in this category are piezoelectrics, thermoelectrics, photovoltaics, pyroelectrics, photoluminescents and others.

Chapter 4 will also consider these types of materials at length. The following list briefly summarizes some of the more common energy-exchanging smart materials.

- Photovoltaic – an input of radiation energy from the visible spectrum (or the infrared spectrum for a thermo-photovoltaic) produces an electrical current (the term voltaic refers more to the material which must be able to provide the voltage potential to sustain the current).
- Thermoelectric – an input of electrical current creates a temperature differential on opposite sides of the material. This temperature differential produces a heat engine, essentially a heat pump, allowing thermal energy to be transferred from one junction to the other.
- Piezoelectric – an input of elastic energy (strain) produces an electrical current. Most piezoelectrics are bi-directional in that the inputs can be switched and an applied electrical current will produce a deformation (strain).
- Photoluminescent – an input of radiation energy from the ultraviolet spectrum (or electrical energy for an electroluminescent, chemical reaction for a chemoluminescent) is converted to an output of radiation energy in the visible spectrum.
- Electrostrictive – the application of a current (or a magnetic field for a magnetostrictive) alters the inter-atomic distance through polarization. A change in this distance changes the energy of the molecule, which in this case produces elastic energy – strain. This strain deforms or changes the shape of the material.

With Type 2 materials, however, we should be aware that use of the term 'material' here can be slightly misleading. Many of the 'materials' in this class are actually made up of several more basic materials that are constituted in a way to provide a particular type of function. A thermoelectric, for example, actually consists of multiple layers of different materials. The resulting assembly is perhaps better described as a simple device. The term 'material', however, has still come to be associated with these devices – largely because of the way they are conceptually thought about and used. Application-oriented thinking thus drives use of the term 'material' here.

SMART SENSORS, ACTUATORS AND CONTROL SYSTEMS

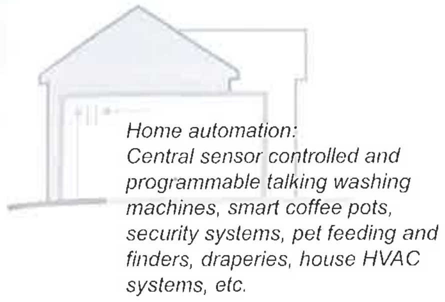
Compounding the problematic of terminology, we will see that many smart materials may also inherently act as sensors or actuators. In their role as sensors, a smart material responds to a change in its environment by generating a perceivable response. Thus, a thermochromic material could be used directly as a device for sensing a change in the temperature of an environment via its color response capabilities. Other materials, such as piezoelectric crystals, could also be used as actuators by passing an electric current through the material to create a force. Many common sensors and actuators are based on the use of smart materials.

In the use of Type 2 materials as a sensor or actuator, there are also different kinds of electronic systems that are integral to the system to amplify, modify, transmit, or interpret generated signals. Logic capabilities provided via microprocessors or other computer-based systems are similarly common. There are several different types of strategies possible here. We will return to this topic in Chapter 5.

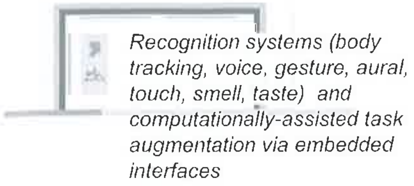
COMPONENTS AND SYSTEMS

As is common in any design context, basic types of smart materials are normally used in conjunction with many other materials to produce devices, components, assemblies and/or systems that serve more complex functions. As was previously mentioned, external walls in a building, for example, provide a range of pragmatic functions (thermal barrier, weather enclosure, ventilation, etc.) as well as establishing the visual experience of a building. Single materials cannot respond to these many demands alone. Thus, we might have a whole series of different types of 'smart walls' depending on exactly how the wall is constituted, what primary functions it is intended to serve and the degree to which there are external logic controls.

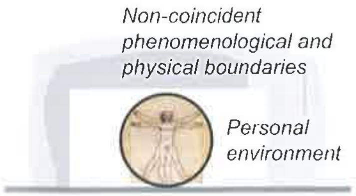
In addition to constructions that we normally think of as components, we also have whole systems in buildings that can be designed to possess some level of smartness. The systems of concern here include normal environmental systems (heating, ventilation and air conditioning; lighting; acoustical) and structural systems. Historically, one of the first uses of the term 'smart' was in connection with improved sensor-based monitoring and control systems for controlling the thermal environment in a building (the 'Smart House' of the 1990s). Whether or not this approach is commensurate with the term 'smart' as it is used today is an interesting question, and one that we will return to in Chapter 7. In that chapter we will consider different kinds of smart systems in use today.



'Smart Home' - Current versions of smart homes depend on automation and information technology



Current 'intelligent rooms' depend on information-rich multimodal environments that are context-aware of occupants



Future approaches will feature increasing cognition and context-aware response levels suggestive of biological models, but may also see an evolution of the personal environment and a devolution of traditional physical and phenomenological boundaries

Figure 1-8 Current smart room and intelligent room paradigms, with a glimpse into the future (*see* Chapter 8)

SMART VS INTELLIGENT ENVIRONMENTS

Fundamentally, the product of architecture and design is a complete work – whether a building or a lamp. Inherent to each, however, is a stunning complexity in all of its aspects. Here the question is naturally raised of the notion of smart and/or intelligent environments. The term 'intelligent' itself is as problematic as the term 'smart', yet it surely suggests something of a higher level than does 'smart'. We do expect more out of 'intelligent systems' than we do from 'smart materials'. Everyday connotations of the term 'intelligent' with suggested notions of abilities to understand or comprehend, or having the power of reflection or reason, could be useful, and will help us as we examine the current conceptions of these environments and develop new ones of our own.

One of the more fascinating aspects of today's society is how 'techno-speak' terms come into existence and assume currency without universal agreement about what is actually meant. There has been a lot of recent interest in 'intelligent rooms' and 'intelligent buildings' without a clear consensus about what is actually meant by these terms. The parallel question raised of whether common rooms or buildings are 'dumb' is equally interesting, particularly since architects and builders have done rather well at responding to societal and cultural needs for millennia. More specific fundamental needs have not been ignored, nor have the wonderful vicissitudes of human desire. So, presumably, something else and more specific is meant by the terms 'intelligent rooms' or 'intelligent buildings', but what? Here we also engage in another meaning conundrum. The phrase 'smart environments' is in widespread use and has already been employed in this book. What, if anything, is the difference between an environment or building space that is 'intelligent' and one that is 'smart?' The engineering and computer science worlds often do not distinguish between the two, presuming that both represent the crowning culmination of technological development – that of the fully contained and controlled environment. In Chapters 8 and 9, we begin to propose an alternative in which systems become smaller and more discrete, freeing our bodies and our environments from an overarching web of control. It is perhaps in this arena that architects can have the most impact on the trajectory of these advanced materials and technologies.

Notes and references

1. All discussion on alchemy in this chapter is from David. C. Lindberg (ed.), *Science in the Middle Ages* (Chicago: The University of Chicago Press, 1978). See in particular chapter 11 on the 'Science of Matter'.
2. Davies, M. (1981) 'A wall for all seasons', *RIBA Journal*, 88 (2), pp. 55–57. The term 'polyvalent wall', first introduced in this article, has become synonymous with the 'advanced façade' and most proposals for smart materials in buildings are based on the manifestation of this 1981 ideal.
3. http://virtualskies.arc.nasa.gov/research/youDecide/smartMaterials.html.
4. Kroschwitz, J. (ed.) (1992) *Encyclopedia of Chemical Technology*. New York: John Wiley & Sons.

2

Fundamental characterizations of materials

Chapter 1 provided a brief insight into how smart materials and systems might affect our design thinking. We identified five 'conceptual' characteristics – immediacy, transiency, self-actuation, selectivity and directness – that differentiated these materials from more traditional materials, but we need further information regarding the 'physical' characteristics of these materials and technologies. For example, how do we measure transiency? Or what defines discretion in an assembly? As designers, we understand conceptual characteristics as intentions, whereas engineers understand physical characteristics as tools in implementation. This chapter will begin to lay out the tangible definitions that are necessary for bridging this gap in knowledge and in application. In order to achieve this we must directly address the question of how best to classify these materials. Classification systems and related taxonomies are useful not only for simple categorization and description purposes, but they can invariably suggest more far-reaching fundamental constructs of a field. This precept is particularly important in our current context in which the smart materials field is just emerging. Examining the structure of different classifications for materials will help us to place smart materials within a broader context. After reviewing several existing and common approaches for classification, we will develop our own structure that marries the intentions of the architect with the tools of the engineer.

The latter half of this chapter will provide the necessary overview of materials science, beginning with atomic structure and concluding with material properties. Fundamental to the development of a new construct for the exploitation of these materials in the design professions is an understanding of the origin and determinants of their behaviors. Just as the responses of these materials are discrete and direct, then our interaction with them must ultimately function at the same scale, whether atomic, molecular, or micro-structural. Designers are used to manipulating materials at the object scale, and while a large-scale interaction will invariably impact smaller-scale behavior, we can operate more efficiently, predictably and quickly if we act directly on the root mechanism of the behavior.

2.1 Traditional material classification systems

There are a number of existing classification and descriptive systems used in connection with materials. One broad approach stems from a fairly basic materials science approach to the subject matter, wherein the primary point of view revolves around the internal structure of the material. Another approach commonly used in the engineering profession is essentially descriptive but focuses on the performance characteristics of materials. In the design fields, a host of different loose categorizations are used, many of which are particular (and perhaps idiosyncratic) to individual fields. For example, interior designers maintain classification types that are distinctly different from those used in landscape architecture. There are also various kinds of classifications that literally provide the legal basis for the specification of materials in design works. In general, we will see that each material system adopts a particular point of view that is useful to a particular construct of the field and/or for a particular application. The construct may have no overlap or applicability for another group. Hence, it is important to understand these points of view.

MATERIAL SCIENCE CLASSIFICATIONS

The material science approach to classification goes directly to the core understanding of the basic internal structure of materials. As a result, we might consider this system to be *compositionally* driven. The most fundamental level of differentiation begins with the bonding forces between individual atoms. It is this bonding force, whether ionic, covalent, metallic or Van der Waals, that will ultimately determine many of the intrinsic properties and major behavioral differences between materials. The next level of description hinges on the way these bonding forces produce different types of aggregation patterns between atoms to form various molecular and crystalline solid structures. These larger aggregation patterns can further be differentiated by how their molecular structures branch or link or, in crystalline solids, by different types of unit cell and related spatial lattice structures such as face-centered or body-centered. Diamond, for example, is a covalently bonded material with a cubic crystal structure. At the highest level are the broadly descriptive categories such as ceramics, metals or polymers, which are familiar to us even insofar as the boundaries between these classes are not nearly as distinct as at the lower levels of the classification system – silicones exist between ceramics and plastics, and many semiconductors could be either a metal or ceramic.

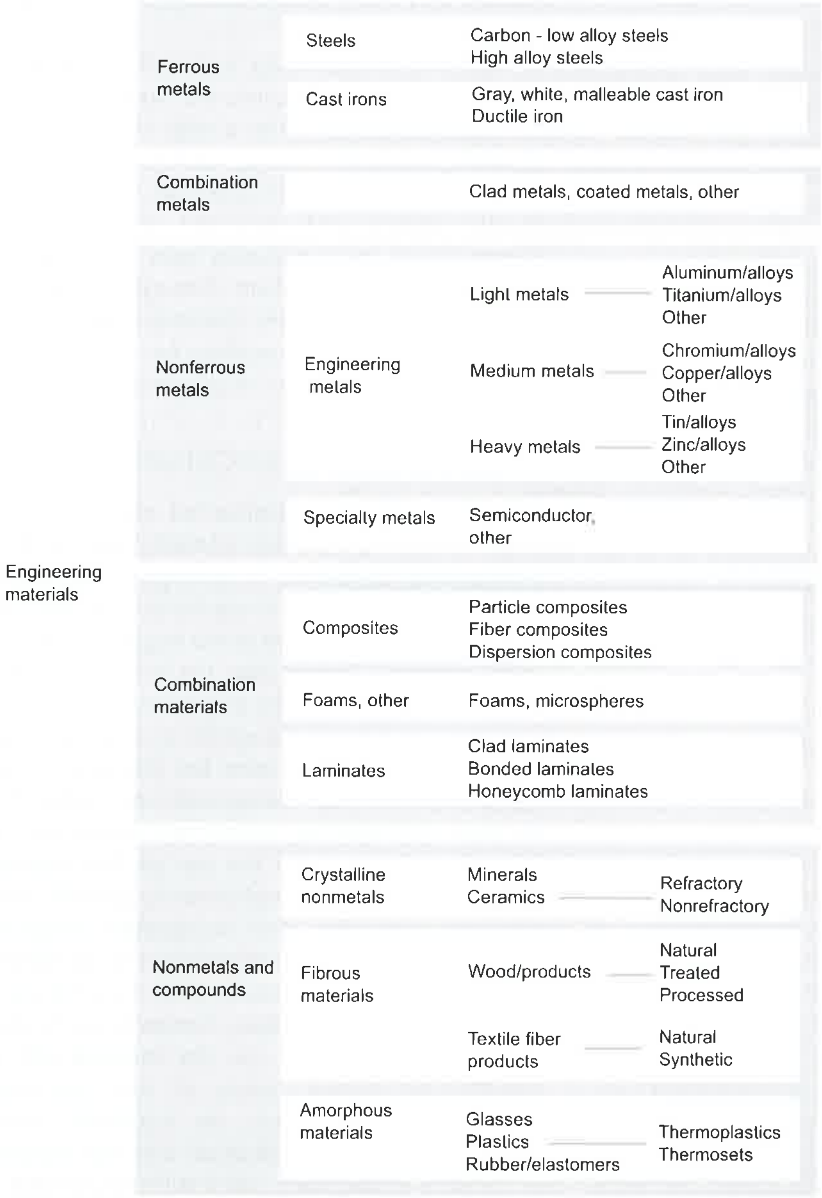
This way of classifying materials is extremely useful for many reasons. In particular, the understandings reflected in the classifications provide a way of describing the specific qualities or properties (e.g., hardness, electrical conductivity) that characterize different materials. Knowledge of properties at the atomic and molecular level can transform our impression of smart materials from 'gee-whiz' materials into an understanding of them through scientifically described attributes and behaviors. Consequently, it also provides a basis for developing a method for designing materials that possess different qualities or properties.

ENGINEERING CLASSIFICATIONS

Applied classification approaches are shown in Figures 2–1 and 2–2. These types are primarily used in the mechanical engineering profession to distinguish between the fundamental *problem-solving* characteristics of the nearly 300 000 materials readily available to the engineer (steel alone has over 2000 varieties). Rather than the hierarchical organization of the material scientist, the engineering classification is one of mapping, enabling the engineer to mix and match properties and attributes to best solve the problem or need at hand. Materials in the engineering realm are chosen based on what they can do, how they behave and what they can withstand. The physical criteria for the use are first determined, and a material is selected or engineered to provide the best fit or, at the very least, the most acceptable compromise for the specific criteria. If the material science classification describes how a material is composed, then the engineering classification explains what it does. Furthermore, since the focus is always a practical one, i.e. the material will be used in a product or process, many of the categories are quite pragmatic. For example, an important category is the environment of the application: can the material function in a corrosive atmosphere, can it withstand being submerged in sea water? Still other engineering classifications might include cost, availability, or recyclability as categories of equal importance to the more basic descriptive ones such as state and composition. Even though the final objective in all engineering applications is the optimization of a material property for a particular situation, regardless of the material type, the additional criteria will quickly narrow down the

STATE	solid, liquid, gas
STRUCTURE	amorphous, crystalline
ORIGIN	natural, synthetic
COMPOSITION	organic, inorganic, alloy
PROCESSING	cast, hardened, rolled
PROPERTY	emissivity, conductivity
ENVIRONMENT	corrosive, underwater
APPLICATION	adhesive, paint, fuel

▲ **Figure 2-1** Basic organization of material catgeories in the engineering profession with a few examples in each category. Engineers must weigh many of these characteristics in choosing a material. (Adapted from Myer P. Kutz (ed.), *The Mechanical Engineer's Handbook*. New York: John Wiley, 1998)



▲ **Figure 2-2** This classification system for materials is typical of those used in applied engineering. It readily mixes the form of material structures (e.g., laminates, amorphous) with properties (ferrous, nonferrous), but can be very useful for many applications. It is difficult to use this kind of classification, however, to describe smart materials with property-changing or energy-exchanging characteristics. (Diagram modeled after Fig. 31-9 in Myer P. Kutz (ed.), *The Mechanical Engineer's Handbook*. New York: John Wiley, 1998)

seemingly endless choices. Many industries have developed their own classification systems to help narrow down the choice of materials to those that are appropriate for their own uses. For example, the American Iron and Steel Institute, which deals only with ferrous materials, adopted a straightforward numbering system that encompasses alloy composition, carbon content and processing method. The American Welding Association is even more specific, categorizing electrode materials by tensile strength, welding technique and position. Regardless of the source of the classification system, each one clearly highlights properties that underpin the useful behavior of the material.

The behavior focus of the engineering classification is not as likely to lead toward the direct development of new materials as would be supported by the more compositionally focused system of the materials scientist. Nevertheless, by working toward the optimization of a property, rather than of a material, this focus on behavior is friendlier toward new materials. Desired behaviors, as defined by material properties, have no preference for specific materials or technologies, and, as a result, will be more suitable for and more open to experimentation and novel solutions.

TRADITIONAL ARCHITECTURAL CLASSIFICATIONS

There are several material classification approaches that have evolved over the years for describing the materials used in architectural settings. Many have a mix of classification perspectives, and are rarely based on pure performance requirements, as would be characteristic in engineering fields. Architectural building codes and standards, for example, often supersede performance criteria in an attempt to simplify the selection process and remove liability for performance failures. For many uses, codes and standards often explicitly or implicitly identify acceptable materials, leaving the architect only to select between brands. As a result, architectural classifications tend to be more nominative – simply listing materials and uses in accordance with standard building requirements.

Within architectural practice, these various requirements are codified in different ways. In the United States, the Construction Specifications Institute has maintained a standardized classification system for over 50 years. This system, known as the CSI index, organizes materials in two ways. The first places the materials typically used in a building into broad classes. In this section, we will find generic material groupings such as paint, laminate and concrete. The second organizes

The CSI Master Format

Division 1	General Requirements
Division 2	Sitework
Division 3	Concrete
Division 4	Masonry
Division 5	Metals
Division 6	Wood and Plastics
Division 7	Thermal-Moisture Protection
Division 8	Doors and Windows
Division 9	Finishes
Division 10	Specialties
Division 11	Equipment
Division 12	Furnishings
Division 13	Special Construction
Division 14	Conveying Systems
Division 15	Mechanical
Division 16	Electrical

Division 8	Doors and Windows
08100	Metal doors and windows
08200	Wood and plastic doors
08250	Door opening assemblies
08300	Special doors
08400	Entrances and storefronts
08500	Metal windows
08600	Wood and plastic windows
08650	Special windows
08700	Hardware
08800	Glazing
08900	Glazed curtain walls

▲ **Figure 2-3** The Construction Specifications Institute (CSI) Master Format is a standard outline for construction specifications in the United States. To illustrate the depth of this format, Division 8 is presented in its expanded form

by component or system. These categories are equally generic and, furthermore, are not even material-specific. For example, windows fall into this category, even though they may be manufactured with wood, vinyl, aluminum or steel. The emphasis in both major groupings is toward application and common use; the fundamental behaviors and properties are incidental. In the broad material classes, the properties, performance and behavior are largely presumed to be satisfactory as long as the chosen material fits within the normative uses defined by practice. For example, the characteristics of wood are discussed in relationship to their relevance for the intended application: the grade of wood suitable for load-bearing roof structures, or the type of wood suitable for finish flooring. The system or component classes focus on application as well. Doors are organized according to their suitability for security, fire protection, egress, as well as by their use for commercial or residential buildings.

The CSI index also addresses the technologies typically used in buildings, grouping them into operational systems, such as heating, ventilating and air conditioning (HVAC), lighting and plumbing, and into constructional systems, such as structural, drainage and vertical circulation. This too differs substantially from the method for categorizing technologies in the engineering fields in which technologies are routinely organized by their process – e.g. smelting or CAD/CAM – or by their mechanism of operation – compression or pumping. Fewer specifics are made available to architects on these systems, as it is presumed that an engineer will be responsible for selecting building technologies.

Essentially, if the materials science classification explains '*why* one material is differentiated from another', and the engineering classification determines '*how* a material performs', then the architectural classifications operates at the other end of the sequence by listing '*what* a material is and *where* it is used'. This system is intended to remove the decision-making responsibility from the architect, and as such, it is less about informed choice and optimization and more about specification and standardization. The result is information, not knowledge.

This general approach is often the framework into which applications of new materials in architecture are forced to fit, and it has clearly proved problematic in this regard. Classification systems such as that of the CSI are not intended to spur innovation in the materials field. Rather, they are practical templates for communication between architects, contractors, fabricators and suppliers. After the preliminary design of a building is completed and approved, architects prepare construction documents that serve as the 'instructions' for the construction of the building. A textual document defines each building element on the design drawings and specifies the material or component. This document, rather than providing guidelines, instead serves as a binding contract that construction professionals and contractors must follow. Trade associations and manufacturers of building products routinely write their material and product specifications in this format to streamline the specification process for architects, and many architectural firms maintain an internal set of construction specifications that are used as the baseline for all of their projects. While communication and contractual applications are important, particularly in a field that has direct responsibility for the public's safety and welfare, the peripheral consequences of a specification-driven system generally result in the exclusion of new and unusual materials and technologies.

2.2 Alternative classification systems

Nevertheless, there have been many attempts to introduce new materials to designers through alternative classification systems. Many are quite qualitative and readily mix approaches to description, but almost all invert the criteria-driven process that characterize the materials science and engineering systems. In many design fields the material is chosen long before performance criteria are defined and as such the process tends to be artifact-driven. The rationale for this comes from many fronts, not all of which are based on physical requirements reflected in the mechanical engineering classification approach or the internal structuring of the material science perspective.

A good example of this general approach is reflected in the book *Technotextiles*, which converges on a specific subset of materials intended for use in the fashion design profession. Terms such as Fibres and Fabrics, Electronic Textiles, Engineered Textiles and Textile Finishes are used broadly to characterize the materials described in the book.[1] These categories are used to describe and illustrate many of the textiles used in the fashion design industry. Several descriptions are by the finishing process (e.g., Heat-transfer, Ink-Jet), some by general composition or form (Laminates, Composites), several by broad designations of material type (Glass, Metal), others by use (Coatings) and still others by geometry (Three-dimensional textiles). Product designers are similarly familiar with Mike Ashby's 'bubble charts', which visually represent material groups and their properties.[2]

To the engineer or scientist, there appears to be no common thread present in this descriptive system, yet it has been very useful to the fashion designer. The thread that is present is not a science-based understanding of the materials described; rather the approach touches on the information needed by the working fashion designer in selecting and using materials – a process in which materials are usually chosen on the basis of certain aesthetic qualities readily understood by the designer (with performance requirements considered afterwards). Current process orientations (e.g., ink-jet), for example, are known to produce particular kinds of visual characteristics known *a priori* to the designer. In this sense, the free mixing of perspectives can be useful and valuable. Nevertheless, a highly problematic aspect of this approach is that it is based almost entirely on current or past practices and thus further codifies them. This approach is also not useful to other groups important to the future of the field, such as to the materials scientist seeking to develop a new kind of polymer that exhibits specific mechanical properties, or to the mechanical engineer seeking to identify a material for use in a product such as an automobile body where performance requirements are paramount.

Material ConneXion®, a material library and resource bank in New York and Milan, attempts to circumvent the resistance to new material adoption in many of the design fields by including only unusual or novel materials in their collection. Most of the 3000+ materials in their collection are unprecedented in architecture, as they come from fields and applications with little crossover. For example, there are ceramic tiles used for furnace refractory lining, and polyamid resins for injection molding. The materials are organized similarly to the broad composition categories that sit at the top of the material science classification system, but are without the inductive lower layers that serve to explain the material. The eight broad categories – polymers, glass, ceramics, carbon-based, cement-based, metals, natural materials and natural material derivatives – also have little in common with the more normative architecture categories. While this is intended to break the hegemony of the currently over-specified process of material selection that abounds in the design fields, there is little contextualization of the categories. For example, the term polymer is not associated either with a familiar product or a particular use. Without an understanding of material behavior and structure, architects and designers fall back to a more familiar mode – choosing a material based on its visual characteristics.

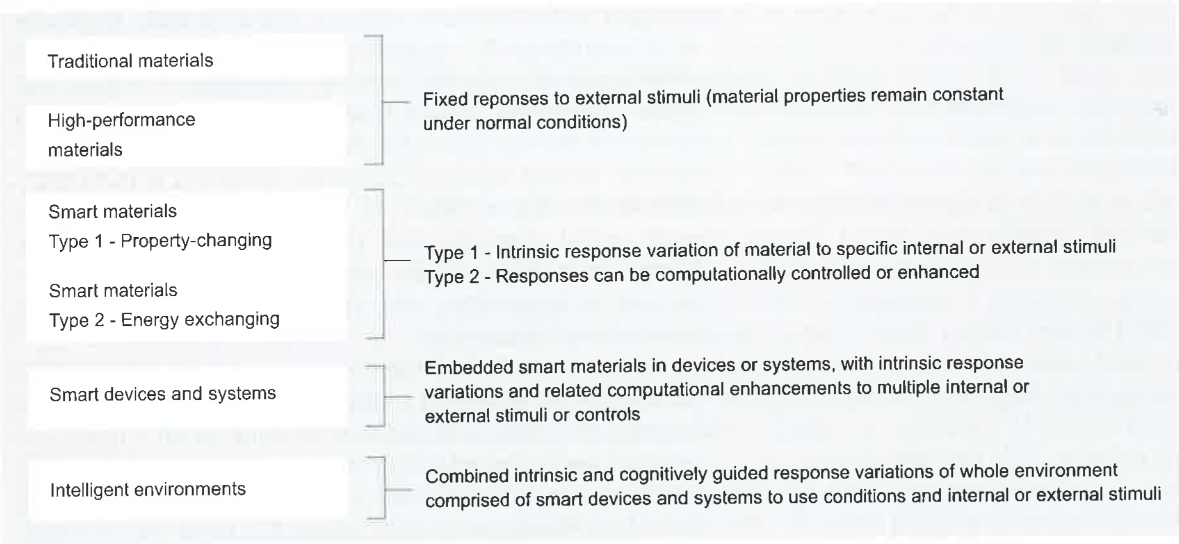
If in the traditional engineering approach the material is understood as an array of physical behaviors, then in the traditional architectural and general design approaches the material is still conceived as a singular static thing, an artifact. Considering smart materials as fixed artifacts is clearly unsatisfactory as this neglects their contingency on their environment (their properties respond to and vary with external stimuli). The engineering approach is little better as it is based on a specificity of performance optimized to a single state that inherently denies the mutability of the material and its interactions with its surroundings. As a result, many of the materials and technologies that we are interested in have not been suitably categorized by other systems, including those of the engineering field.

2.3 Classification systems for advanced and smart materials

The information necessary for the implementation of new materials may be available, but there is as yet no method for its application in the design fields. Staying with the current method and treating smart materials as artifacts in a classification system is clearly problematic. Even if a smart material could be considered as a replacement for a conventional material in many components and applications, its inherent 'active' behavior makes it also potentially applicable as a technology. For example, electrochromic glass can be simultaneously a glazing material, a window, a curtain wall system, a lighting control system or an automated shading system. In the normative classification the product would then fall into several separate categories rendering it particularly difficult for the architect to take into consideration the multi-modal character and performance of the material. Furthermore, many of the new technologies are unprecedented in application, and thus have no place-holder in conventional descriptions.

Perhaps most fitting, then, is for smart material classifications to be multi-layered – with one layer characterizing the material according to its physical behavior (what it does) and another layer characterizing the material according to its phenomenological behavior (the results of the physical behavior). Phenomenological behavior is rarely documented, much less considered, in the field of architecture. We can categorize these effects in terms of their arena of action, which could be considered as analogous to an architect's intention – what do we want the material to do? The smart materials that we use can produce direct effects on the energy environments (luminous, thermal and acoustic), or they can produce indirect effects on systems (energy generation, mechanical equipment). This approach is operationally very useful to the designer in evaluating the use of smart materials and systems in relation to the design of environments.

We must also recognize, however, that there is both value and reality in considering how these materials are invariably used in the service of making ever-more complex devices, assemblies and environments that are intrinsically multi-modal or otherwise provide more complex responses than are possible with single materials. This is essentially a functions/systems approach. As noted in Chapter 1, this book follows a bi-partite approach: materials and technologies are categorized by behavior – both physical and phenomenological – and then overlaid with increasing component and system complexity. This layer enables us to meet and confront related new initiatives and technologies that shape larger devices and environments – especially those initiatives on 'intelligent environments' that spring primarily from the computational world. Here we must address questions previously raised about how smart materials relate to the world of intelligent devices and environments. As a way of structuring subsequent inquiries and discussions, a working classification approach based on function/system overlay is shown in Figure 2–4. The figure describes a proposed organization that establishes a sequential relationship between materials, technologies and environments. Cognizant of the need for contextualization, this organization also maintains the fundamental application focus of the more traditional classification system. We will see later that this approach presents other difficulties, but it nevertheless provides a useful way of approaching the subject. The organization of this book, then, mirrors the organization of our proposed classification system.



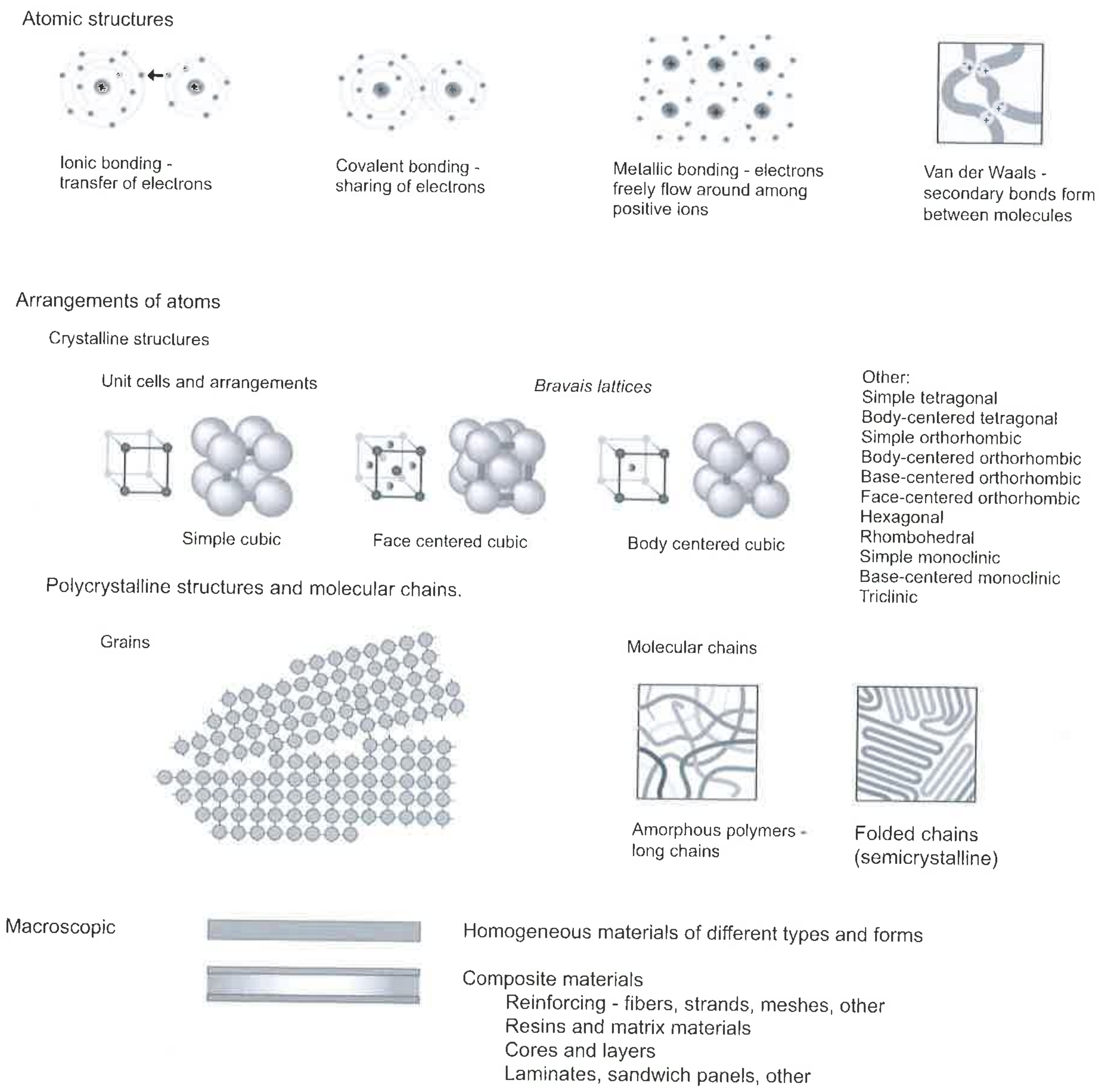
Traditional materials High-performance materials	Fixed reponses to external stimuli (material properties remain constant under normal conditions)
Smart materials Type 1 - Property-changing Smart materials Type 2 - Energy exchanging	Type 1 - Intrinsic response variation of material to specific internal or external stimuli Type 2 - Responses can be computationally controlled or enhanced
Smart devices and systems	Embedded smart materials in devices or systems, with intrinsic response variations and related computational enhancements to multiple internal or external stimuli
Intelligent environments	Combined intrinsic and cognitively guided response variations of whole environment comprised of smart devices and systems to use conditions and internal or external stimuli

▲ **Figure 2-4** Distinguishing smart and intelligent systems and environments

2.4 The internal structure of materials

Regardless of the classification system used, designers must be exposed to the essential determinants of material behavior. Knowledge of atomic and molecular structure is essential to understanding the intrinsic properties of any material, and particularly so for smart materials. In this section, we begin by briefly reviewing several important topics essential to this understanding. We will see that there are various ways solid materials are composed into the major categories of crystalline solids, amorphous solids and polycrystalline solids. For example, crystalline solids have an orderly and repetitive arrangement of atoms and molecules held together with different types of chemical bonding forces. These patterns form regular lattice structures, of which there are many different types with corresponding material structures. Amorphous solids have a random structure, with little if any order to them, and also have little intrinsic form. Polycrystalline solids are composed of large numbers of small crystals or grains that are in themselves regular, but these crystals or grains are not arranged in any orderly fashion. The precise makeup of these different internal structures and the bonding forces between them largely determine the mechanical, electrical, chemical and other properties of the solid material that are so important in design applications. For example, we have seen earlier that the 'color' of a material depends both on external factors (e.g., the wavelengths of the incident light) and on the material's internal absorption characteristics, which in turn are dependent on the specific organization of the atomic structures that comprise the material.

In order to understand how these different internal structures ultimately determine the resultant properties of materials, it is useful to first look at the different kinds of bonding forces that exist between collections of atoms that ultimately comprise the basic building blocks of any material. Subsequently, the ways individual atoms aggregate into crystalline, amorphous or polycrystalline structures will be reviewed.



▲ **Figure 2-5** General structures of materials at the micro and macro levels. The structure of a material at each of these levels will strongly influence the final characteristics and properties of the material

BONDING FORCES

At the most fundamental level, we know that an atom consists of three subatomic particles – electrons, protons and neutrons. Electrons revolve at different distances around a positively charged nucleus formed of protons and neutrons. The negatively charged electrons exist at different energy levels in 'shells'. While most of the mass of an atom is concentrated in the nucleus, the nature of the electron cloud is the most significant determinant of the resulting properties. The electrons in the outermost shell are the valence electrons and these are the ones that can be gained or lost during a chemical reaction.

Some atoms do have stable electron arrangements and can exist as single atoms – these are the noble gases. More typically, however, atoms tend to bond to one another to become electronically more stable, consequently forming crystals and molecules. Bonding forces that develop among constituent atoms or molecules hold these larger structures together.

The three primary atomic bonds that develop among atoms are ionic bonds, covalent bonds and metallic bonds. Ionic bonding involves one atom transferring electrons to another atom, covalent bonding involves localized electron sharing and metallic bonding involves decentralized electron sharing. Some secondary atomic and molecular bonds also exist, of which the Van der Waals forces are of primary interest.

In ionic bonding, one atom transfers electrons to another atom to form charged ions. The atom that loses an electron forms a positive ion (electropositive) and is normally considered a metallic element. The one that gains an electron forms a negative ion (electronegative) and is normally considered a non-metallic element. Oppositely charged ions attract one another. The forces associated with ionic bonding thus involve the direct attraction between ions of opposite charge.

Multiple ions typically form into compounds composed of crystalline or orderly lattice-like arrangements that are held together by large interatomic forces. The positive and negative ions form into specific structures whose geometry depends on the elements bonded (crystalline structures are discussed in more detail below). Common table salt or sodium chloride (NaCl) has an ionic bond, as do metal oxides. Ionic compounds are solid at room temperatures, and their strong bonding force makes the material hard and brittle. In the solid state, all electrons are bonded and not free to move, hence ionic solids are not electrically conductive (electricity is normally carried by freely moveable electrons). Solid materials based on ionic bonding have high melting points and are generally transparent. Many are soluble in water. In the melted or dissolved state, electrical conduction is possible because both states involve conditions that free up electron bonds and make them moveable.

When atoms locally share electrons, covalent bonds are produced. For example, two atoms share one or more pairs of electrons. Unlike ionic bonding, neither atom completely loses or gains electrons. There is a mutual electrical attraction between the positive nuclei of the atoms and the shared electrons between them. This kind of bonding frequently forms between two non-metallic elements. The bonds occur locally between neighboring atoms thereby producing localized directions. In some instances, small covalent arrangements of atoms or molecules can be formed in which individual molecules are relatively strong, but forces between these molecules are weak. Consequently, these arrangements have low melting points and can weaken with increasing heating. They are also poor conductors of electricity. In other instances, such as carbon in the form of diamond, it is possible for many atoms to form a large and complex covalent structure that is extremely strong. These covalent solids form crystals that can be thought of as a single huge molecule made up of many covalent bonds. In diamond, for example, each carbon atom is covalently bound to four other carbon atoms in a tetrahedronal fashion. Covalent structures of this type of structure are normally very hard, have very high melting points, will not dissolve in liquids and, because electrons are closely bound and not free to move easily, they are typically poor electrical conductors.

Metallic bonds are closely related to covalent bonds in that electrons are again shared, but this time in a non-localized, non-directional nature. These kinds of bonds exist in metals such as copper. A characteristic of a metallic element is that it contains few electrons in the outer shells (either one, two or three). Their outer shells are thus far from full. Immediate sharing with localized neighbors will not be able to fill this shell. Rather, electrons in the valence shell are shared by many atoms instead of just two. These shared electrons are not tightly bound to any one atom and move freely about. The forces of attraction between these mobile electrons and the positive metal ions hold the material together. These forces are known as metallic bonds. As a consequence of these forces, the ions tend to arrange themselves in close-packed orderly patterns. These kinds of metals conduct electricity well because of the freely moving electrons. (If a voltage is applied, the electrons move readily – electrons can enter the arrangement and force others out, yielding a current flow). These same arrangements are also good heat conductors, again because of the free electrons. As will be seen later, the same arrangements often allow the material to deform in a ductile way.

A final bonding force to be considered – the Van der Waals bond – occurs between individual molecules. In many materials, particularly polymers, individual molecules are made of covalently bonded atoms and are consequently quite strong. Due to the normal imbalance of electrical charges between molecules, small attractive forces – the Van der Waals bonds – are developed between them. These secondary bonding forces are relatively weak by comparison to ionic, covalent and metallic bonds. They can break easily under stress and they allow molecules to slide with respect to one another. Ice crystals, for example, are strong H_2O molecules bonded to one another by Van der Waals bonds, but heat or pressure causes these bonds to break down, resulting in liquid phase water.

In summary, the atomic bonding forces determine many of the properties of the final material. These forces are by no means equally strong. In general terms, ionic bonding is the strongest, followed by covalent bonding, metallic bonding and, finally, Van der Waals bonds, which are the weakest of all. While defining material types solely by bonding forces alone is not adequate, we can none the less still observe the following: (1) metals are materials characterized by metallic bonds; (2) ceramics are polycrystalline materials based on ionic and/or covalent bonds; (3) polymers have molecular structures (chains of atoms) that are covalently bonded, but with the chains held together by Van der Waals forces. Further differentiations will be discussed below.

CRYSTALLINE SOLIDS, AMORPHOUS SOLIDS AND POLYCRYSTALLINE SOLIDS

The physical structure of materials is characterized by the arrangement of their atoms, ions and molecules. In the discussion above, it was noted that individual atoms typically bond to one another to become electrically stable and form larger structures. The characteristics of the individual atoms that are bonding, and the kind of bonding force that exists among them, largely determine the way that they aggregate. For example, it was noted that in diamond each carbon atom is covalently bonded with four others to produce a tetrahedronal arrangement. This basic arrangement can be repeated many times over to create a large crystalline structure.

Atomic arrangements in a crystal are described by the spatial network of lines defined by the location of atoms at the intersection points. The idea of a unit cell that specifies atom positions is used as the conceptual building block of a crystal since it forms a basic repetitive unit. The characteristics and geometry of the unit cell are determined by its basic atomic structure. A crystalline structure is made up of large number of identical unit cells that are stacked together in a repeated array or lattice. The shape or geometry of the resulting crystal depends in turn on that of its constituent unit cells. A close study of the geometry of unit cells reveals that there are really only seven possible basic types: cubic, tetragonal, orthorhombic, rhombohedral, hexagonal, monoclinic and triclinic. These basic cells can then be replicated to form identifiable larger lattice structures. Basic morphological considerations indicate that there are 14 basic lattice structures (known as Bravais Lattices) that can be made from the seven basic unit cells (some basic unit cell types can repeat themselves in multiple ways). For example, one of the basic lattices is called a face-centered cubic lattice. In this lattice, atoms are located at the eight corners and the centers of the six faces. Copper, for example, has a face-centered cubic lattice. By contrast, in a body-centered structure there is a single atom at the center of each unit cell with others at the corners or sides of the cell. Tungsten, for example, is a body-center cubic structure, as is iron. Other lattices have different arrangements that in turn can be identified with different real materials. Many typical metals, for example, have either a face or body-centered cubic structure, or a close-packed hexagonal one. Titanium, for example, has a hexagonal close-packed structure, as does zinc.

A particular crystalline structure can become quite large in physical terms. For a number of reasons, however, the growth of a crystalline pattern is interrupted and a grain is formed. A grain is nothing more than a crystalline structure without smooth faces. Many materials are composed of large numbers of these grains. Particular grains meet one another at irregular grain boundaries and are normally randomly oriented to one another. Grain size can vary due to multiple reasons. Metal-working procedures – including heat treatment, cold working or hammering – alter grain size and orientation (changes are visible in a microscope). Alterations in the grain structure can in turn produce changes in material properties (e.g., ductility, hardness).

In a more general sense, it is important to note that material properties are affected not only by the type of

crystalline structure present and the macro-structural properties such as grain arrangement, but also by other factors. It is extremely important to note that a pure crystalline arrangement can have enormous strength. Based on studies of bonding strengths and lattice arrangements, material scientists can calculate so-called 'theoretical strengths'. Actual tests of very small ideal specimens (often called 'whiskers') reveal that actual strengths can match theoretical strengths. Early tests on tiny tin crystals demonstrated strengths of over a million pounds per square inch. Even tiny glass fibers, for example, demonstrated tensile strengths of up to 500 000 psi (3450 Mpa) – a value that is about six times higher than that of high-strength steel.

Tests on larger specimens, however, suggest that these maximum strengths cannot normally be obtained. This is because of the normal and expected existence of micro-defects in lattice structures. These include point defects (missing atoms), line defects (a row of missing atoms), area defects (including grain boundaries previously noted) and volume defects (actual cavities). All of these variations from the perfect lattice typically cause changes in the properties of materials, particularly metals.

Line defects, typically called 'dislocations', are particularly important in understanding the differences between theoretical strengths and actual strengths. A missing line of atoms might cause a line defect, or the inclusion of an extra line that in turn causes an opening in the crystalline structure. Under the application of a stress, these dislocations actually move through the structure of the crystal.

Materials in which dislocation movements freely occur are normally very ductile (i.e., they deform plastically very easily). Typical processes of rolling, casting and subsequent heat or mechanical treatments of larger material pieces can create literally millions of dislocations in a crystalline structure. These same processes also affect grain size and other characteristics. Together, the properties (e.g., strength, ductility, malleability) of many common metals are strongly influenced.

Other materials cannot be similarly characterized. As will be discussed more below, many polymeric materials are long chain molecular structures. The individual polymeric chains themselves are normally covalently bonded and quite strong. The connections, however, from chain to chain are held together by weaker Van der Waals bonds. Long chain molecular structures can be cross-linked or folded, which in turn gives the final material different characteristics and properties.

PHASES

Many of the materials that we are interested in have multiple phases, of which the major ones are gas, liquid and solid. We are familiar with the phase transformations as ice melts or as water vapor condenses. These phase changes occur because of changes in their temperature or surrounding pressure. Besides these major phases, many materials have transition states that produce incremental phase changes as the material undergoes a change in its environmental conditions. Iron, for example, has a particular crystalline structure (BBC or body centered cubic) at room temperature. Its phase in this normal state is called ferrite. Upon heating to above 1644 °F the internal structure of iron changes to a new crystalline form (FFC or face-centered cubic) that is called austenite. It undergoes yet another phase change at around 2550 °F since above this temperature austenite is no longer a stable form of iron. This final phase just before melting temporarily reverts back to a body-centered cubic structure. Mechanical and other properties change as the material undergoes each of these phase transformations.

Phase diagrams are used graphically to represent what phases or states exist in a material at different combinations of temperature, pressure and composition. In a pure element, such as iron, composition is not a variable. In alloys, including steel, the precise composition of metals making up the alloy is a critical factor in determining how the mixture varies under different temperature and pressure states. Phase diagrams require some experience in learning how to read them, but they are a common tool of the chemist and materials scientist in understanding the behavior of materials under different conditions.

2.5 Properties of materials

Materials are often distinguished by their properties, some of which are intrinsic and some of which are extrinsic. An intrinsic property is determined by the molecular structure – essentially the chemical composition – of the material. As such, the definition of a specific material also defines all of its intrinsic properties. For example, strength is related to the interatomic forces within the molecule in conjunction with the intermolecular forces that form the material structure: the higher the forces, the greater the strength and hardness of the material. These same forces also directly correlate with the substance's melting and boiling points. A material like diamond, with strong interatomic and intermolecular forces,

is not only one of the hardest materials in existence, but also has an extraordinarily high melting point. Besides strength, commonly recognized as intrinsic are a material's mechanical properties, including elastic modulus, and toughness, its physical properties, including conductivity, specific heat and density, and its chemical properties, including reactivity, valence and solubility.

Extrinsic properties are those defined by the macro-structure of the material and as such cannot be directly determined by the composition alone. The optical properties of a material – reflectivity, transmissivity, absorptivity – are often extrinsic as are many acoustic properties. Simply polishing the surface of a metal will produce a substantial change in its reflectivity. Several extrinsic properties are also dependent upon the characteristics of the energy fields of their environment. The color of a material is not a property of the material *per se*, as it is completely dependent on the spectral distribution of the incident light.

Property changes, then, can be produced either by an alteration of the composition of the material or by an alteration in the micro-structure of the material. Both alterations are initiated by an energy input to the material. Input energy can be in many forms of which the most common for smart materials include electrical, chemical, thermal, mechanical and radiative. While most materials undergo similar property changes with an input of energy – for example hot rolling steel changes its microstructure and therefore its properties – smart material changes are also reversible: when the energy input is removed, the material reverts back to its original properties.

All material properties, whether intrinsic or extrinsic, smart or 'dumb', fall into one or more of five categories. The categories – mechanical, thermal, electrical, chemical and optical – are indicative of the energy stimuli that every material must respond to. Although we will study energy stimuli in depth in Chapter 3, a few basics now will be helpful in developing a qualitative understanding of the deterministic relationship between a material and its properties. All energy stimuli are the result of 'difference'. A difference in temperature produces heat, a difference in pressure produces mechanical work. Properties are what mediate that difference. As such, we will note that properties generally have units that reflect the nature of the difference.

Mechanical properties determine how a material will behave when subjected to a load or a mechanical force. That load may be produced by a weight, a shear force, impact, torsion, or a moment, and the behavior that results from these loads includes strain, deformation, or fracture. The mechanical properties determine what result will be produced, and to what degree, by the application of a specific load. Mechanical properties depend on the type of interatomic bonds present, the arrangement of atoms, their larger-scale organizations, the presence of dislocation mechanisms, and gross physical characteristics such as grain size and boundaries. These factors are in turn influenced by material type and composition, including alloying, and if the material is subsequently treated or processed (e.g., annealing, tempering or work-hardening for metals). Mechanical properties are described by specific measures. Strength is a measure of a material's resistance to forces and is commonly described in terms of failure or yield stress (force per unit area) levels. Strain is a deformation measure. Stiffness is a measure of the stress-deformation characteristics of a material. For materials with linear stress-strain characteristics, the Modulus of Elasticity is a useful descriptor of the stiffness characteristics of a material. There are different failure stress levels and elastic moduli depending on the state of stress (tension, shear). Additional mechanical properties of interest include a material's ductility or brittleness, malleability, toughness, hardness, fatigue limits, creep characteristics and others. These properties are discussed at length in many other books.[2]

Electrical properties of primary interest include a material's conductivity and resistivity. Conductivity – the ability of a material to conduct electrical current – is so important that materials are often classified by this property into conductors, semiconductors and nonconductors (insulators or dielectrics). Resistivity is the inverse of conductivity. Materials with a lot of free electrons (e.g., metallic bonded materials) are good conductors since the free electrons become carriers of electrical current. In general, the conductivity of a material increases with lowering temperatures. Superconductivity refers to a phenomenon in materials below a certain critical temperature where resistivity almost vanishes. Special semiconductor materials, however, can behave differently wherein conductivity can increase with rising temperatures (see Chapter 4). Magnetic properties are closely allied to electrical phenomena and properties. Computer disks, motors and generators, credit cards, etc., all are based on magnetic phenomena. Depending on how the material responds to a field, magnetic materials are classified as ferromagnetic, antiferromagnetic, ferrimagnetic, diamagnetic and paramagnetic.

Thermal properties of fundamental significance include a material's thermal conductivity, heat capacity and thermal expansion. Thermal conductivity in conductive materials, such as metals, can be largely explained in terms of the free electron movements discussed earlier. Thermal energy in the form of rapid atomic lattice movements is transmitted through a material via electron movements from the hot to the cold end. Thermal conductivity in dielectric (insulating) materials is a more complex action as it occurs through vibratory phenomena since few or no free electrons exist. Heat capacity is a measure of the amount of heat needed to be transferred to a material in order to raise its temperature a certain amount. Thermal expansion refers to the amount of dimensional change that occurs in a material as a consequence of a temperature change. Most materials, with the notable exception of water changing to ice, tend to shrink with decreasing temperature levels.

Chemical properties of particular interest include a material's reactivity, valence and solubility. Reactivity is a measure of how a material chemically acts with another substance to produce a chemical change. The term solubility generally refers to the capability of a material for being dissolved (a solvent, in turn, is a material, usually liquid, that has the capability of dissolving another substance). The term valence generally refers to the capacity of an element to combine with another to form molecules.

The optical properties of a material, such as its reflectivity, transmissivity and absorptivity, are complex since they may depend upon both intrinsic and extrinsic factors. When light is incident on a material, it is either re-emitted via reflection or transmission, or it might be converted into heat energy. These phenomena are closely dependent on the nature of the material's electron field at its surface (see Chapter 4).

2.6 General classes of materials

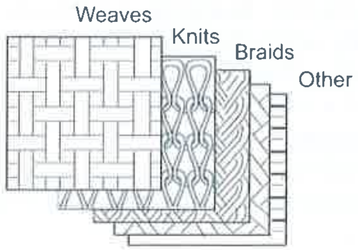
Briefly, there are three primary material classes – metals, ceramics, polymers – and many related or derivative types fall into a fourth type known as composites.

Pure metals, including copper, are characterized by their metallic bonds and regular lattice structures. Many metals having face-centered cubic organizations are quite ductile because external forces easily cause slipping among planes that have preferred directions. Iron and nickel are transitional metals involving both metallic and covalent bonds, and tend to be less ductile than other metals. Dislocations and related phenomena are of extreme importance in understanding how metals behave.

REINFORCING

Reinforcing materials
- Glass fibers
- Polymer fibers
  - Organic (e.g., Kevlar)
  - Nylons, polyesters, etc.
- Carbon fibers

Organization of reinforcing
- Basic forms
  - Strands, filaments, fibers, yarns (twisted strands), rovings (bundled strands)
- Weaves, braids, knits, other
- Nonwoven mattings
- Films, sheets
- Other



RESINS AND MATRIX MATERIALS

Resin materials
- Epoxies
- Polyesters
- Vinyls
- Other

CORES

Core materials
- Foams
- Balsa
- Synthetic fabrics
- Other

Organization of cores
- Honeycombs
- Laminates
- Other

▲ **Figure 2-6** General makeup of composite materials intended for high performance strength or stiffness applications

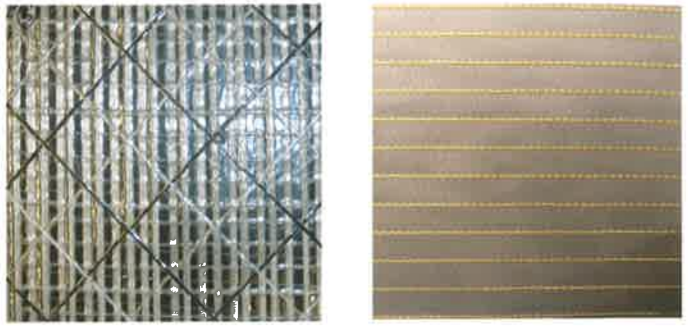
Ceramics are characterized by their strong ionic and covalent bonds. Since there are no free electrons that move around, these materials have crystal structures that are electrically neutral and are not good conductors. Dislocation movements are present in ceramics but are of lesser importance. In general, ceramics are hard and brittle, and tend to fail along special cleavage planes. Consequently, ceramics are normally very hard and brittle. They have high resistance to heating and are often used as refractory materials. Glass is an amorphous non-crystalline structure linked by covalent bonds.

Polymers are composed of long-chain molecular structures. Individual molecules are covalently bonded. In simple *thermoplastics*, the chains are not directly connected but are bound together only by weak van der Waals bonds. Hence, they are quite soft and ductile since external forces can cause chains to slide by one another relatively easily. These same thermoplastics can be easily melted (heat breaks down the van der Waals bonds) and will then reform into a solid when cooled. Thus, they can be easily recycled. *Thermosets*, by contrast, have additional hardeners added to them that cause the long-chain molecules to be cross-linked or interconnected. Common epoxies are thermosets. External forces cannot cause chains to easily slide by one another. Consequently, these materials can be quite strong and hard. They cannot, however, be melted like thermoplastics.

Folded chain polymers have a periodic arrangement of chains in them that are crystalline in nature, but not cross-linked, and have multi-layered structures to them. They can be formed in many ways, including crystallization from dilute solutions. These semi-crystalline polymers can be quite dense. They can be made chemically resistant and highly heat resistant. In Chapter 4 we will see that this class of polymer is particularly important *vis-à-vis* smart behaviors since the semi-crystalline nature of these folded chains allows many properties to be imparted to them that are not normally associated with polymers (e.g., conductivity).

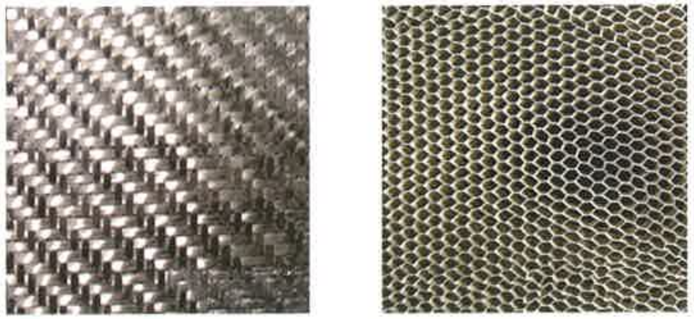
Elastomers are polymers that have largely amorphous structures, but are lightly cross-linked. They can be thought of as laying between thermoplastics and thermosets. Many natural materials are elastomeric whereas other elastomers can be readily synthesized. The Vulcanization process – used in making common automobile tires – creates cross-links containing sulfur atoms. The rubber gives the tires elasticity, but the cross-linking makes them sufficiently stiff and hard.

Composites are high-performance materials that are made by combining two or more primary materials. They comprise a huge class of materials – there are literally thousands of them – and are beyond the scope of this treatment to discuss in detail. Briefly, composite materials are invariably intended for high-performance applications where their properties are engineered for specific purposes, and they may be broadly thought about in terms of their functions. Are they intended to serve strength or stiffness functions? Are they meant to reduce thermal conductivity? Are they meant to have special reflective characteristics? Figure 2–6 shows the general makeup of composites intended for strength or stiffness applications. Normally, these composites are made up of reinforcing materials, resins or matrix materials that the reinforcing materials are embedded into, and, quite frequently, internal cores are present as well. Different forms of these kinds of composites can be engineered for specific strength or stiffness applications, including directions of stresses and so forth. For other purposes, embedded materials



Reinforced polymer Dacron/Kevlar fabric

▲ **Figure 2-7** Two flexible composite sheets

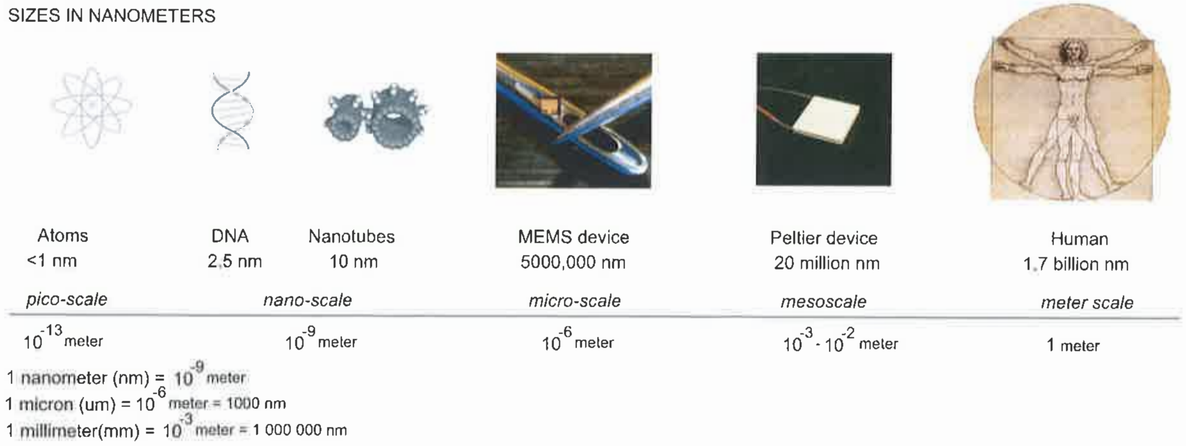


Carbon fiber sheet Aluminum honeycomb core

▲ **Figure 2-8** Typical materials used in composites may not serve strength functions at all. Fiber-optic cables, for example, have been embedded in different materials to serve as strain or crack detectors in the primary material. Also, different films or sheet products may be laminated together as well. The high performance radiant color films with multiple reflectance qualities, for example, are multi-layered laminates of different types of films.

2.7 Nanomaterials

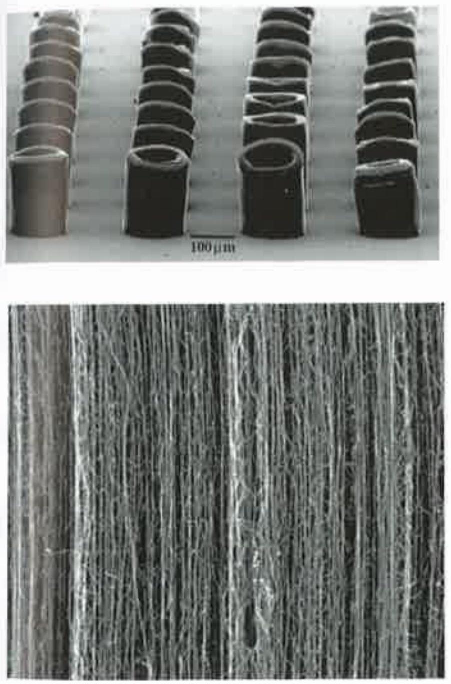
The term 'nanotechnology' has attracted considerable scientific and public attention over the past few years. The prefix 'nano' indicates that the dimensional scale of a thing or a behavior is on the order of a few billionths of a meter and it covers a territory as large, if not larger, than that represented by micro-scale. For comparison, the head of a pin is about one million nanometers across whereas a DNA molecule is about 2.5 nanometers wide. Given that individual atoms are nanometer size (for example, 5 silicon atoms is equivalent to one nanometer), then the ability to build structures one atom at a time has been a provocative objective for many materials scientists. In its simplest form, nanotechnology conceptually offers the potential to build 'bottom up,' creating materials and structures with no defects and with novel properties.



▲ **Figure 2-9** Relative size comparisons. Nano-scale objects exist at sizes near the atomic level. Micro-scale objects, such as many MEMs devices, are much larger (a human hair, for example, is about 50 µm in diameter) and can be visually seen. Devices at the meso-scale level (equivalent to millimeter to centimeter scales) are relatively large in comparison to microscale and nanoscale objects, but still very small with respect to human dimensions

As discussed earlier in this chapter, the precise makeup of different internal structures and the bonding forces between them largely determine the mechanical, electrical, chemical and other properties of the solid material. Nanotechnology, by enabling the complete construction of the molecular structure, may afford us the possibility to design unprecedented and dramatically enhanced properties for the macro-scale. Indeed, it may even be possible to produce substantially different properties without even changing the chemical composition. Already, one nanomaterial – carbon nanotubes – has been attributed with an electrical conductivity that is 6 *orders of magnitude* higher than copper, and a strength to weight ratio that is 500 times greater than that of aluminum.[3] Essentially, we will be able to *program* material properties. Furthermore, constructing bottom up could also allow for self-assembly, in which the random (non-continuum) motion of atoms will result in their combination, or for self-replication, in which growth occurs through exponential doubling.

Beyond the opportunity to 'build' materials from scratch, nanotechnology also encompasses the development of and application of nano-sized materials and systems. Nanoparticles are being proposed for inclusion in paints and abrasives, and nanoprobes are intended to be the basis of *in vivo* drug delivery devices. Quantum dots – nanometer-sized semiconductor crystals capable of confining a single electron – represent the next generation in luminescent technology as they essentially are quantum LEDs (light-emitting diodes). The potential applications for nanotechnology abound, from data storage to body armor, but this exciting field is still in its infancy, and many of proposed application domains are, at best, speculative. Nevertheless, both the technologies and ideas implicit in thinking about behaviors at the nano-scale hold great promise for the future.



▲ **Figure 2-10** Carbon nanotubes (CNT). A tubular form of carbon, with a diameter as small as 1 nm, is produced from sheets rolled into tubes. (NASA Ames)

Notes and references

1. Braddock, S. and Mahoney, M. (1998) *Technotextiles.* London: Thames and Hudson.
2. See, for example, Schodek, D. (2003) *Structures*, 5th edn. Englewood Cliffs, NJ: Prentice-Hall.
3. These numbers came from a presentation titled 'An Overview of Recent Advancements in Nanotechnology', delivered by M. Meyyappan of NASA Ames Research Center in October 2002. The numbers vary widely from source to source.