CHAPTER 4

INFORMATION IS A MATERIAL

> All these dotcom people, you know what they really want to be doing? They want to be working with wood.
>
> *Chicken John Rinaldi*

Once, aluminum was a precious metal. The tiny amount known to exist was used only for the most exclusive decoration. In 1884 the builders of the Washington Monument, then the world's tallest man-made structure, capped it with the world's largest block of aluminum, which weighed 3 kg (about 6.5 pounds). To the builders, this block symbolized America's mineral and technological wealth more than gold or platinum. About a year later, two chemists discovered how to use electricity to extract aluminum from bauxite. Aluminum soon was seen as the most common metal on earth.[1] By 1900, the United States alone produced thousands of tons each year (US Bureau of Mines, 2007). Once aluminum was inexpensive and widely available, it became a favorite design material. Aluminum appeared in everything from soda cans, to bicycles, airplanes, and underarm deodorant.

A similar thing is happening to computers. When information processing was expensive, companies focused on the single precious processing unit. Thanks to Moore's Law (Chapter 1), information processing has become inexpensive and widely available, much closer to the building blocks in a monument than a precious jewel on top.[2] It is nearly as easy to incorporate information processing into a mass-produced object as it is to create a custom injection-molded plastic part. The capability to collect, organize, and manipulate information has become a component instead of the goal of digital product design.

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[1] There had been a number of methods for extracting aluminum in the early nineteenth century, but all of them were very expensive. In 1886 Charles Martin Hall developed a new process in America that lowered the price of extraction significantly (on the order of two orders of magnitude). Almost simultaneously, Paul L. T. Héroult developed a similar process in France, and the process was named the Hall-Héroult process.

[2] Weiser (1991) made a similar analogy, but rather than aluminum, he references the history of electric motors. He argues that much like electric motors disappeared into appliances at a certain price point, computation stops being the focus of design when it gets cheap enough. Kline (1996) wrote about the 1918 Sears "Home Motor," a generic household electric motor. Sears expected a family would buy one motor and then buy attachments for it that could beat eggs, grind metal, run a fan, etc. This is the same relationship that personal computers had with peripherals: one CPU and many attachments. Kline further expanded on Weiser's point when he wrote: "Hardly obsolete, the Home Motor is instead a victim of its own success, ignored precisely because of its ubiquity. It has become a central — albeit invisible — fact of daily life. Can it be that, as the electric motor goes, so goes the Internet?"

Information processing no longer needs to be the purpose of an object, but one of many qualities that enables it to be useful and desirable in ways that are more directly related to people's wants and needs. In other words, information processing no longer defines the identity of an object, but is one of many materials from which objects can be made.

Once information is considered a design material, it becomes possible to ask a whole range of new questions about it:

- What are the properties of information as a design material?
- How can information processing be used by designers?
- How well is information processing used today? Can better use be made of it?
- Will adding information processing create a better functional experience? A better esthetic experience?

Much like a traditional design process can weigh the advantages of using an expensive and difficult material (say, carbon fiber) with one that is cheap and easy (say, aluminum), looking at information processing this way may tell us when *not* to use it. Sometimes a smart component can perform better than a standard one, and vice versa.

For example, Rafi Haladjian points out[3] that the toy industry has fully embraced information processing as a material to create competitive advantage. Tyco's Tickle Me Elmo doll, a runaway success in 1996, depends not only on its resemblance to a Sesame Street character, but on its behavior — an infectious laugh and flailing limbs — which was created by an embedded processor, sensors, and a voice chip. Without the behavior the doll would be just a red plush toy. Since then, every holiday season has brought more sophisticated toys that depend on behavior for their competitive advantage. The current edition of Tickle Me Elmo has dozens of behaviors, reactions, and phrases it can deploy in different situations. The designers of these toys are not treating information processing as the focus of the toy, nor are they portraying the toy as "a computer" or implying typical "computer-ness" in the design. Instead, they treat information processing as a material that enables the core focus of the design: the toy's behavior.

4.1 A SHIFT IN DESIGN THINKING

Treating information as a material requires approaching the user experience design of a device as a single thing, rather than one made of disjoint pieces.

For example, a disassembled mobile phone (Figure 4-1) says little about what it does. Looking at the pieces by themselves, a casual observer may not be able to tell whether they made a phone, a calculator, a TV remote, a thermostat, or

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[3] Private communication, 2006.

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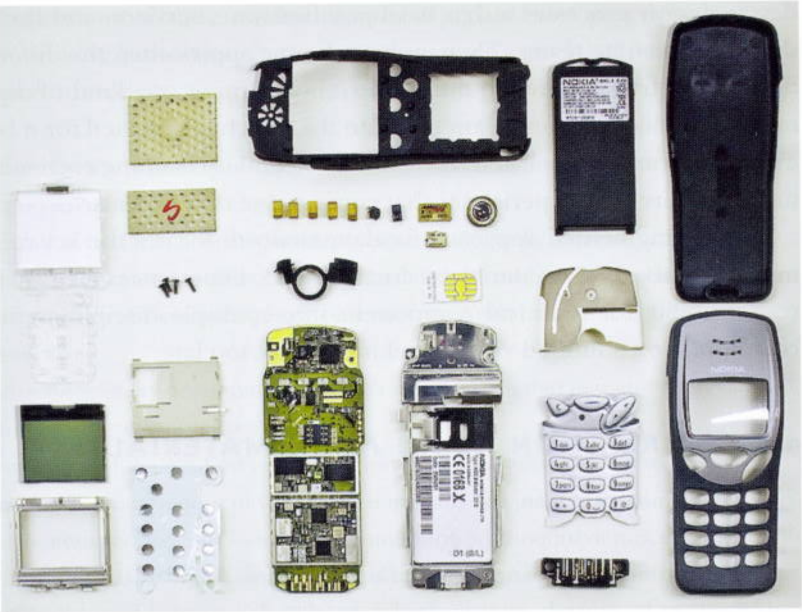

Figure 4-1

A disassembled phone. (Photo © Johannes Henseler, licensed under Creative Commons Attribution 2.0, found on Flickr)

any number of other devices with a keypad and a screen. The numbers on the chips identify some functionality, but even with close examination, figuring out that the phone can send a text message would be almost impossible.

This functionality becomes hard for humans to see when the phone is disassembled, because digital information is invisible to human eyes. Yet digital information processing is the key component that makes the phone what it is. Digital information processing is more critical than the rubber in its buttons or the glass of its LCD screen. The information is not abstract: it is in the phone's firmware and the data the phone stores, communicates, and manipulates. It is additional software people have loaded on the phone, and how the software encodes the social networks of the user. Those are the things that differentiate a mobile phone from a calculator, a TV remote, or (as often happens with old phones) a paperweight.

The separation of design tasks into narrow fields like electronic hardware engineering, industrial design, software development, and content creation is artificial.[4] This division of labor has made the design of information largely invisible from the outside,[5] leaving no one wholly responsible for it. Typical

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[4] I hypothesize that this is the product of the complexity of the tools each of these disciplines developed in the 1980s and 1990s. These tools were primitive and required a high degree of domain-specific knowledge, leading to specialization. This was not always the case, of course, and there are many examples of early computer hardware, software, and information designed by the same people or small groups working together in close collaboration (Levy, 1994).

[5] It may be difficult, and possibly undesirable, to make information processing more visible. Information processing embedded in computational devices is genuinely difficult to experience directly, unlike the device's mechanics or the industrial design of its affordances. Turkle (1984) did early research with kids and electronic devices where she found that understanding where the behavior of electronics originates is very difficult. Making the mechanics of information flow more visible may be fundamentally difficult and impractical in many situations, just as the flow of gasoline in an internal combustion engine is not necessary to successfully drive or design a car.

device design processes assign hardware, software, services, and the industrial design to separate teams. Then, as launch time approaches, the different teams desperately try to unify the disciplines, shoehorning one kind of digital information produced by one team task into the structures created for it by another. The pieces rarely fit well and the teams often end up blaming each other for any unsatisfactory user experiences that come out of that process.

Such a fragmented approach fundamentally dislocates the key role of information as the core material in creating user experiences. It distributes the responsibility for a critical component into multiple disciplines that do not collaborate on a unified vision until it is almost too late.

4.2 INFORMATION AS AN AGILE MATERIAL

> As technologists, then, our concern is not simply to support particular forms of practice, but to support the evolution of practice — the "conversation with materials" out of which emerges new forms of action and meaning.
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> *Paul Dourish (2004)*

Just as most consumers do not spend much time differentiating which parts of a device are made of glass, metal, or silicon, they do not spend much time identifying which effects they experience are created by hardware, software, or by services. They see the device as a single thing. To them, a button press is not a specific amount of pressure on a certain kind of rubber that closes a switch that triggers a firmware response that launches software that connects to a network. Instead, it is the beginning of a conversation with a friend. Nevertheless, information pervades every aspect of the designed object, a deep part of the encounter between humans and machines that produces its effects.

This singular user perspective implies that distinctions between the disciplines that created this device are artificial and may be unnecessary. It implies a shift in attitude to the process of design, to the sequence in which the experience is created, and to whom is involved at what stage. Designing with information requires a process that unravels many assumptions of the past to weave a new process that is highly interdisciplinary, iterative, integrated, user-centered, and social.

This sounds like a daunting task, and it is. Fortunately, user experience design has a model for this kind of process: agile software development.

The core of most agile software development practices (Highsmith, 2001) is a set of social practices centered on the negotiation between what is known about what users need, the interdisciplinary development team's understanding of it, and the limits of the chosen technologies. It is explicitly designed to blur the distinctions between stages of development to mirror the way that software is experienced, just as what is required when designing with information as a material.

At the core of most agile methodologies is a cluster of practices that are looped over and over, sometimes as frequently as once a week, to build a product from the core out, similar to growing an organism:

- A user-centered articulation of a need or desire (by representative actual users, user-generated data, or experts) is necessary.
- A negotiation to clarify how that need can be technologically expressed. This is created by frequent, often daily, highly focused discussions between technology creators (designers, developers, engineers, etc.), program managers, and user representatives.
- The cross-disciplinary development of a technological solution that minimally satisfies what has been agreed upon as a solution.
- The evaluation of the solution in terms of how well it functions from a technical and user perspective.

This is analogous to Bill Buxton's practice of *Sketching User Experiences* (2007): the process of iterative sketching, which creates devices of ever-greater conceptual complexity and definition without committing the development team to a rigid, fragmented process.

Design is as much the process of discovering constraints as creating within them. Considering information processing in dialog with all other materials in a highly iterative, interdisciplinary process, it is possible to generate design ideas, explore possibilities, and uncover constraints that would have been difficult to articulate otherwise.

For example, an office furniture company decides to create an LED office desk lamp, and they want the lamp to be dimmable to satisfy a key user need. In an iterative development process hardware engineers tell the rest of the group early on that fading an LED is not as simple as fading an incandescent lamp. It requires a technique called pulse-width modulation, which typically requires a processor. This choice is as transformative on the capabilities and constraints of the lamp as the LED choice was in the first place. Because LEDs run cool, the lamp will not have the heat dissipation problems they would have with a halogen, but LEDs are more difficult to both focus and diffuse than halogen, creating a new set of challenges.

Similarly, once the team has chosen to use a processor in the lamp, information has been introduced as a material. Along with pulse-width modulation, processors enable reactive behavior. The processor can parrot the fading behavior of a dimmer switch and also dim the lights in response to the brightness of the room. If the team uses RGB LEDs, the lamp can change the color of the light based on the current weather, giving the light on rainy days a warmer, sunnier tone. Deciding how to best use these capabilities requires group design decisions about the physical design of the lamp. Does automatic dimming address any known user needs or desires? If so, where will the light sensor go? If the lamp reacts to the weather, how will it know what the weather is like?

Whether or not to include any of these functions becomes less a question of technological capability or expense, since both are relatively minor compared to other components in the lamp. Instead, it becomes a point of team negotiation around the use of a single (if critically important) material: information.

4.3 THE PROPERTIES OF INFORMATION

If information processing is a new design material, what are its properties? What can designers do with it and how can they do it?

4.3.1 INFORMATION REQUIRES A MEDIUM

Although digital information can be described in isolation, it requires other materials to be experienced.[6] In this format it resembles electricity. Just as we cannot experience electricity without employing conductors, information requires other media to be used in design.

Vallgårda and Redström (2007) proposed "computational composite" as a term to describe the melding of information with a traditional material "to become a material we can use in design practice." For example, glass that is coated with a film that changes color in response to electrical signals sent by an attached processor[7] is fundamentally different than just coated glass that has no processor attached. Similarly, a simple electric motor is a different design material than a servo, which is an electric motor that has processors and sensors permanently attached to it and controlling it. Motors are controlled electronically or mechanically, while servos must be controlled digitally. This effect is so strong that the combination of the two materials, the computational composite, becomes a design material in its own right, just as reinforced concrete (which couples steel rods with concrete) is treated as a single material.

The study of smart materials (see Sidebar: Smart Materials) is based on this fundamental capability of information as a material.

As with all physical materials, new properties and applications continuously emerge. Designers regularly create new uses for old material, and new materials appear with such regularity that material libraries (Figure 4-2) exist to familiarize designers with them.

Traditional materials (steel, plastic, or cotton) have properties such as elasticity, strength, resistance to corrosion, etc., but digital information has none of these inherently.

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[6] Löwgren and Stolterman (2004) described information as a "material without qualities," with few inherent attributes that can be used in design, but which acquires attributes as part of the design practice.

[7] Electrochromic glass (Ritter, 2007).

Figure 4-2

A materials library. (Photo © 2007 by Kate Andrews, used with permission)

Those qualities it does have draw on physical properties of the electrical forms of information such as digital bits, optical flashes, or analog current.

But if we are to work with digital information as a material, we need at least some initial properties that prompt creative thinking. Unfortunately, there are few systematic overviews of information as a design material. The following list is based on my own experience over the past five years working with digital information as a material. Instead of attempting to define the properties of "pure" information, I have found it most useful as a designer instead to organize my thinking based on common challenges of instantiating electrical information into new devices.[8] This list is divided into three sections: capabilities, possibilities, and constraints.

- Capabilities. As a design material, digital information has a number of inherent capabilities that are (largely) derived from the properties of electronics and, more specifically, computers.
- Possibilities. Information processing enables certain design techniques more easily than others, and produces better results than other techniques or materials. These are the inherent possibilities.
- Constraints. Designing objects that use digital information creates challenges that designing with other materials does not, such as the design constraints imposed by information.

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[8] Pure information also has properties. These are described by *information theory* and include things such as entropy, noise, bandwidth and the encoding used to describe it, and the probability that a sequence of received bits is the same as the ones transmitted. From a design perspective, starting at this level is akin to starting with particle physics when the immediate task calls for drilling a hole. Information theory is fascinating, but it is rarely applicable in experience design projects.

Most things made with information processing exhibit these properties, although not all of them may be interesting or valuable in all situations. This is true about all material properties; for example, flammability is an inherent property of wood that rarely figures significantly in furniture design (with a few notable exceptions). The point of this list, and the point of describing information as a design material in the first place, is to help designers conceptualize embedded computation as an extension of experience design.

Note: This section owes a significant debt to Löwgren and Stolterman (2004), Addington and Schodek (2005), and Ritter (2007).

4.3.2 CAPABILITIES

These form a base on which other properties of information as design material rest. Some of the capabilities listed here are, of course, not exclusive to information, but are things that electronic information processing does more easily or more efficiently than other approaches. For example, although it is possible to perform complex mathematical calculations mechanically, it is much easier done with electronics.

4.3.2.1 External Phenomena Can Be Translated into Electrical[9] Information

Sensors for light, pressure, location, heat, sound, movement, chemicals, and many other things[10] convert those physical phenomena into information. Similarly, input affordances such as buttons, dials, and keyboards are sensors for human intention. Such sensing can be coupled to create information-induced behavior in the device.

4.3.2.2 Electrical Information Can Be Translated to Physical Phenomena

Motors, heaters, lights, and other forms of output convert information to physical phenomena that can be perceived by people and act on the environment. Coupled with sensors, these actuators form the feedback process by which designers can work with information as a material.

4.3.2.3 Electric Information Maintains State

Smart things remember. The memory may be quite limited, but any information storage maintains a degree of knowledge about the state of the device and its environment.

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[9] I talk about information stored and communicated using electricity, but there are other ways to transmit information. Light (as in photonic computing), magnetism, even carrier pigeons (IETF RFC 1149), can all be used to transmit, store, and process information. However, for the foreseeable future most information will be processed electronically.

[10] Wilson (2005) listed hundreds of sensors and their applications.

Memory enables the material to keep a record of its state at a point of time in the past. This allows devices made with information to function not just in reaction to what is happening in the moment, but what has happened before. It is difficult to make an adjustable chair that can reconfigure itself to settings it had earlier, much less allow selection from a number of different settings that existed in the past. Yet that is exactly what adjustable car seats do because they are, in essence, chairs made with information.

4.3.2.4 Electric Signals Can Be Copied and Transmitted Exactly

Though vexing to the music industry, the most transformative quality of information is that it can be duplicated exactly and transmitted flawlessly (or nearly so), thanks to the many data integrity schemes devised over the years.

From a user experience design perspective, this means that replicating media across space and time is relatively straightforward and inexpensive. Many people can experience the same media at the same time. Many different devices, things that look nothing like each other, may display the same media — albeit in slightly different forms. Sequences can be replayed and replicated.

Communicating information means that devices are not dependent on information locally available. In addition to everything known locally, data physically located elsewhere affect local behavior, and it in turn can induce effects elsewhere.[11]

4.3.2.5 Information Is Fast

Devices integrating information processing can react faster than people can perceive. Even slow computers (by 2010 standards) can react much faster than the basic level of human perception. If basic human reaction time is about 0.1 second (Card et al., 1983), then a processor running at the relatively slow rate of 30 MHz (such as the ones described in Chapter 1) executes 3 million instructions in the amount of time it takes for a person to react to it.

This allows devices made with information to generate behaviors very quickly, in theory. In practice, today's development tools do not allow developers to fully utilize much of the processing power available to them. Modern development tools put layers of abstraction between the "bare metal" of information processing and the tools used to create software to make software easier to write and less error prone. This slows down the apparent speed of certain kinds of processing, but there is still enormous potential for experiences that appear near instantaneous.

4.3.3 POSSIBILITIES

The history of devices made with information processing is already rich with possibilities inherent in information as a design material. Virtually any device that information processing is added to becomes a fundamentally different

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[11] It is this property that enables *cloud computing* or *distributed computing*, where the effects of information processing occurring in one physical location can be experienced in another.

thing (for better or for worse). The list below attempts to identify several of the core design possibilities that information processing enables.

4.3.3.1 Information Enables Behavior

Objects made with information do not act as would be expected if only their physical design was examined. From a user experience perspective, this puts things made with information processing into a category closer to animals or people than to traditional machines.

Mechanical behavior often exhibits visually traceable relationships between causes and effects not present in information behaviors. If a bicycle crank is turned, it pulls a chain that turns a gear. Given sufficient time, it is possible to disassemble a pocket watch to determine how it functions. However, no visual examination of wiring between a pushbutton and a metal box with electronics reveals that the device is an electronic parking meter. This is because the parking meter's core function, its utility, is in how it uses information.

4.3.3.2 Devices Made with Information Can Change

As anyone who has used a coin in place of a screwdriver can attest, people change how they use tools; however, tools rarely change their fundamental capabilities on their own. Adding a new blade to a Swiss Army knife is rare, yet devices made with information regularly update core functional capabilities through firmware updates or new software.

Devices made with information can change dynamically both in real time and in response to requests or circumstances.

4.3.3.3 Information Manipulates Knowledge

Computers can manipulate symbols that have meaning to people, so things made with information processing can affect human knowledge by manipulating symbols that represent that knowledge. Design with information processing can use knowledge that represents specific things that interest people. Previous tools, even ones primarily associated with knowledge (such as printing presses) performed little autonomous knowledge manipulation. Things with information are different. Because they can manipulate information on their own, they can produce knowledge in ways that devices made with traditional materials cannot.

Thus, a paper calendar can do nothing with the appointment notes written on it, but a digital calendar has enough knowledge about human timekeeping and has scheduling activities to automatically update the information stored in it.

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4.3.4 CONSTRAINTS

Every material has inherent constraints. Material science is largely the identification of the limits of various materials across a wide array of dimensions. Information as a material inherits all of the constraints of the electronic materials it is amalgamated with. Electrical computers, for example, should not get wet. Of these constraints, two stand out: its use of power and how it's embedded in electronics that cannot be divided and mixed like a raw material.

4.3.4.1 Information Requires Power

Requirements for electrical power drive many of the decisions made using information as a material and significantly constrains how it is used. Available power has wide-ranging influence on the size, shape, and capabilities of devices. Electrical energy is stored in batteries, generated nearby (through solar, mechanical, chemical, or other means), or acquired from an electrical grid.

The choice of power source constrains how much information can be processed, how much can be sensed, and how much can be transmitted (especially wirelessly). Moreover, each choice brings with it a set of physical constraints: batteries take up space and electronics produce heat that needs to be dissipated. Additionally, batteries must be either recharged or properly disposed of, creating additional demands on users throughout use and beyond. Though ostensibly an engineering consideration, power requirements create a ripple of user experience design constraints as fundamental as color and elasticity do for traditional materials.

4.3.4.2 Information Is Chunky

It is currently not possible to treat information as a homogeneous material, such as a bolt of cloth or a bucket of plastic pellets. As Vallgårda and Redström (2007) elegantly put it:

> A computer [...] cannot physically be cut in half and still exist as a computer. Thus, where a traditional material's threshold for being diminished lies at the point where the molecular structure would no longer exist as a structure or where the fibers (e.g., in wood and textile) are no longer fibers, the threshold for the computer is where its structure needs to be intact. The computer's threshold, therefore, lies at a much higher point on the physical scale.

To include information processing in a device currently requires clumps of electronics spread throughout a device or environment. Even as information processing devices shrink and it becomes possible to physically distribute them in a medium (like pigment in a paint), engineering techniques have not matured to the point where it's possible to easily take advantage of such widely distributed information processing. Until that changes, computing will be embedded as large clumps of functionality inside inert (from an information processing standpoint) materials.

Sidebar: Smart Materials

This chapter presents information as a design material in largely metaphorical terms. However, many people are working to create materials that literally use information processing. Such materials combine the chemical and physical properties of traditional (if sometimes exotic) substances with embedded information processing. Addington and Schodek (2005) defined smart materials as "highly engineered materials that respond intelligently to their environment."

They also enumerated some fundamental characteristics of smart materials:

- Property change. One example is the ability to change color or temperature.
- Exchange of energy. The material can either add energy to a system (as a form of informational output or to do work) or subtract it (as input or, for example, to cool an environment).
- Reversibility/directionality. The ability of these materials to change their properties or exchange information with a degree of symmetry. For example, a piece of traditional metal can be bent and will stay bent unless it is manually unbent; a smart metal can be bent, but can unbend itself (to some degree) on command.
- Size/location. "A component or element composed of a smart material will not only be much smaller than a similar construction using more traditional materials but will also require less infrastructural support."

Smart materials are engineered in a variety of ways to have interesting physical characteristics, not necessarily using electronics or information. When combined with information, smart materials can be referred to as computational composites (Vallgårda and Redström, 2007), or as transitive materials (Coelho et al., 2007).

Examples of such information-enabled smart materials include:

- Luminescent fabrics that glow and change their appearance in response to electronic signals
- Inks that change color, emit smells, or absorb certain chemicals when triggered by electricity or heat
- Polymers with electrical properties that change based on how they are distorted by pressure or heat
- Fluids that change their viscosity based on electrical or magnetic signals

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- Plastics that change their adhesion properties in response to electronic or chemical signals
- Carbon fiber that changes its resistance based on strain, acting as both a structural member and a sensor

The practical uses for such materials expand continuously. Buildings that change shape based on environmental conditions, clothes that change color, and wallpaper that acts as an enormous display are all projects that have been proposed. It is already possible to buy household windows that can be signaled to change transparency and the East Japan Railway Company installed piezoelectric ceramic floors to generate electricity from people's movement (Ogasawara, 2008).

Although the combination of smart materials and ubiquitous computing is still in its infancy, it represents the most exciting user experience possibilities of all.

4.4 WORKING WITH THE MATERIAL PROPERTIES OF INFORMATION

> Products and buildings, for example [have been] described as frozen software. Pervasive computing begins to melt them. Ubiquitous computing spreads intelligence and connectivity to more or less everything. Ships, aircraft, cars, bridges, tunnels, machines, refrigerators, door handles, lighting fixtures, shoes, hats and packaging. You name it, and someone, sooner or later, will put a chip in it.
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> *John Thackara (2000)*

Designing with information as a material is not called out as explicitly in the rest of this book as it is here, but it underlies the ideas that weave through the whole book. This chapter tries to articulate some ideas so that designers can begin to discuss the use of information processing as a tool for experience design. Currently, the design of devices made with information processing is treated differently than the design of devices without it. A device with some chips in it is sold as "consumer electronics," whereas another device made of many of the same materials, but without chips, is sold as "housewares." Each category carries assumptions, which is why consumer electronics made of cotton or ceramics are almost unheard of, yet those materials are common in housewares. One of the intentions of this chapter is to underscore how unnecessary those distinctions are.

Information can be incorporated into objects in a number of ways. The discussion of smart materials by Addington and Schodek (2005) (see Sidebar: Smart Materials) contains a classification that helps distinguish ways that information can be coupled with traditional materials. Their classification (Table 4-1) is a spectrum: from traditional materials with none of the properties offered by information to intelligent environments that include many kinds of smart materials.

Table 4-1

A Spectrum of Information Use in Design with Smart Materials

Classification	Description
Traditional materials and high-performance materials	Fixed responses to external stimuli (material properties remain constant under normal conditions)
Type 1 smart materials: Property-changing	Intrinsic response variation of material to specific internal or external stimuli
Type 2 smart materials: Energy exchanging	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 or controls
Intelligent environments	Combined intrinsic and cognitively guided response variations of the whole environment comprised of smart devices and systems to use conditions and internal or external stimuli

From Addington, M.D. and Schodek, D.L., *Smart Materials and New Technologies*. Architectural Press, 2005. With permission.

Thus, it is possible to talk about a nearly infinite range of ways to use information as a material, from having a tiny amount that enables a single, specific behavior at a specific time to enormous, all-enveloping environments entirely made with electrical impulses. Of course it is possible to go overboard. Enthusiasm for plastic led optimists (and plastic companies) to build houses entirely from plastic,[12] but that does not mean it was a good idea. However, we now live with many things that are made with various kinds of plastics. Using information as a material becomes part of a design process to determine where it is appropriately used, what it is good for, the best way it can be used, and how it can present a danger.

I use the above list of properties (Section 4.3) to trigger consideration of what embedding computation in devices could do well, or poorly. There are no clear guidelines (yet) about when there is just the right amount of information in a project, when there is not enough, and when there is too much. This happens through many years of design exploration and experimentation, just as it did with aluminum. Now that information has become such an inexpensive material, that exploration can finally begin.

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[12] See Heckman (2008) for a lively discussion of Modernist "smart" homes that were also largely made of plastic.