Introduction

Our concepts of sustainable architecture often implicitly draw from images of the vernacular. An earth sheltered home with passive systems is considered the pinnacle of sustainability whereas a speculative office building with a glazed façade would be its nadir. Lower energy is commonly associated with buildings whose forms are directly determined from local climatic conditions while those buildings with sophisticated and complex systems are routinely seen as energy hogs. Smart materials, as a class of advanced technologies, occupy a murky middle ground between the low tech and the high tech approaches: while clearly very sophisticated, these materials are presumed to be direct and discrete substitutes for much larger systems. As such, there has been much hope placed on smart materials as delivering the elusive solution to the intractable problem of ever increasing energy use by building systems.

The faith in smart materials as sustainable substitutes for conventional materials and systems may be misplaced, however, and may instead cause the field of architecture to miss out on the unprecedented opportunities possible if the characteristics of these materials were to be fully exploited. The following presentation sets forward the argument that the true potential of smart materials lays in their instrumentality for manipulating physical phenomena and not in their application within the confines of building performance.

Art & Technology

Few would associate the practice of sustainability directly with art, even insofar as many artists may choose to express points of view about sustainability through the subject of their work. If the questions of the process are foregrounded rather than the message of the subject, then some fundamental learnings could be gleaned about how things work, and in particular, about how physical phenomena are manipulated in the most direct manner. From 1967-1971, the Los Angeles County Museum of Art operated a program that brought together “the incredible resources and advanced technology of industry with the equally incredible imagination and talent of the best artists at work today.” The intention was that mutual benefit would be derived from the collaboration. The artists who participated included such luminaries as Andy Warhol, Claes Oldenberg, Richard Serra and Jean Dubuffet, and the corporations represented the aerospace, scientific research and media industries. Perhaps most remarkable was that the Nobel prize physicist, Richard Feynman, served as a consultant.
Many of the artists treated their paired industries not as collaborators but as unpaid contractors whose only role was to facilitate the artists’ works. An interesting exception was the team between two situationalist light artists—James Turrell and Robert Irwin—with the Garrett Corporation, an aerospace company that primarily designed high performance jet engines but that also had a research department devoted to developing life support systems for manned lunar flights. Before meeting with Garrett, Irwin had prepared a list of materials and phenomena that he was interested in studying, most of the listed items had a direct connection with environmental behavior and sensory experience. Materials with optical properties dominated the list, and he also noted that he wished to study more about shadow images, chemiluminescence or electroluminescence, and “light, color, weight and density in the open air.” Dr. Ed Wortz, who was director of Garrett’s Life Sciences Department, was fully engaged in developing a path of study that explored new territory for all of the collaborators. The intended project was to manipulate sensory perception by initially depriving one of both aural sensation via an anechoic chamber and visual sensation through the means of the Ganz field effect and then reintroducing carefully controlled stimuli. The resulting installation did not come close to meeting the original expectations, consisting instead of a symposium taking place in a room with scrim covered window scrim and cardboard seating, but the impact of the collaboration and investigations of the later work of both Irwin and Turrell was clearly far-reaching. While their later work did not use smart materials, both artists designed for perception by directly manipulating physical phenomena. Indeed, in the formal notes that Turrell kept during the program, there is a profound statement about the role that technology will play in their continuing work.

“Technology is merely a means—not an end. Technological instruments are extensions of ideas…”

The Material Lexicon

If smart materials are to be understood as instrumental, i.e. the “means” as Turrell wrote, then the normative material categorization used in architecture misses the mark. Materials in architecture are commonly treated as artifacts: things that have specific and fixed attributes. Naming the material names its appearance, its performance and its range of applications. The term wood denotes functions quite different from the term metal and also visually connotes qualities, such as domesticity, that would not be typically associated with use of metal. Hardwood flooring will have a particular color and texture, and will withstand a specific amount of bending and impact loading. A glazed curtain wall may be designed to visually dematerialize the exterior of the building, while providing a predictable and measurable quantity of daylight to the interior. In this mode, the material is the effect, and as such, it is often foregrounded. This coupling of material with effect is reflected in our classification systems, whether organized by material—metal, wood, concrete—or by end use—tile, roofing, cladding. Our classification systems, such as the Construction Standards Institute categories (CSI), group these artifacts into a familiar and finite set of materials with which there is collective experience and for which there is extensive documentation.

It is through this lexicon that “smart” materials have entered the profession of architecture. While definitions as to smartness abound, the most generalized one is that smart materials are transformative: the transformation may be within the material itself, as in one of its properties or its physical state, or the material could be the vehicle to transform other things, such as energy forms or the surrounding environment. These are materials, then, whose most salient descriptor is motion. Even though this is starkly counterintuitive to the inherent stasis of conventional materials, we have tried to shoehorn smart materials into our normative categories. Any smart material with a transparent or translucent state is placed in the glazing category, and any light emitting material is dispatched to the electric lighting category. We do this to increase our comfort level with their use. When something like an electrochromic is placed into the glazing category, we understand it and thus use it as a substitute for glass, albeit a very expensive substitute. We specify it in the same sizes and shapes as glass; we justify its expense relative to standard glazing by comparing their performance. A smart material becomes but one of many choices for a given end use.

This subordination of the material to what we know and to how we do things often prevents us from exploiting the truly remarkable characteristics of these materials.
2.12 Smart Materials and Sustainability

Thermo-dynamic Materials

As materials of motion, all smart materials involve an energy transfer in some form or another for transformation to take place. The type of energy that is transferred determines how the material state – temperature, pressure, density or internal energy – will change. The quantity of energy that is transferred to produce this change is determined by the properties of the material. This relationship governs the behavior of all materials, including smart ones.

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\text{change in state \times material property} \times \text{energy transferred}
\]

In conventional materials, the properties scale the relationship between state change and energy transfer. For example, a material’s specific heat (property) will determine how much heat (energy) is needed in order to change its temperature by a specified amount. From the deflection of a material under a structural load, to the color that a material appears to be, the relevant material properties will produce repeatable results. Smart materials add a wrinkle to this predictability in that the relationship is no longer scalar or linear. A material’s property might shift to another value, an energy input might turn into a different form of energy.

Depending upon what is changing and what drives the change, we can group smart materials into four categories:

1. A change in state produces a change in the material property. A thermochromic material reflects a different color when the temperature changes. The material state of temperature determines the material’s property of spectral reflectivity. In this category, we will find many of the color-changing materials, including chemo-chromic (driven by a change in chemical species), mechano-chromic (driven by a change in pressure), and liquid crystals (driven either by a change in temperature or chemical concentration).

2. An energy input produces a change in the material property. A photo-chromic material changes its spectral transmissivity (the ability for light to pass through it) when radiation (light) transfers into the material. This category also describes electro-chromics (an input of electrical energy), and many of the viscosity changing materials such as electro-rheological (also an input of electrical energy), and magneto-rheological (application of a magnetic field).

Figure 3: Everyday items that incorporate smart materials

Figure 4: Active smart materials
3. An energy input is transformed into a different energy output. A photovoltaic converts an input of radiation into an output of electricity. Most of the semiconductor-based smart materials are in this category and include thermo-electrics (thermal energy into electrical energy), piezo-electrics (mechanical energy into electrical energy), and light-emitting diodes (electrical energy into radiation).

4. A change in state produces another change in state (internal energy) that transforms properties and the energy output. Shape memory alloys are one of the more provocative members of this category: when the temperature of the alloy changes, the material undergoes a crystalline phase change (internal energy) that produces an output of mechanical energy (strain). Many of the phase-changing materials are in this category, including smart gels (concentration changes internal energy resulting in mechanical energy).

Mapping behaviors

Designing with smart materials is essentially just mapping the relationships between energy forms and state changes—the material is only the medium for the exchange. One designs for a given output or effect from a given input. Any number of transformations can create a given effect, any number of materials can facilitate the given transformation. As an example, privacy screens and glazing are among the most popular applications of smart materials in architecture. Key to designing a privacy screen is not the selection of a particular material, but the knowledge of what the conditions are and what the result must be. Do was one want to block or obscure image? Does one want light to be intense or ambient? We can produce the desired effect by any of the following: altering the spectral composition of the light, diffusing or redirecting the light, diminishing or changing the angle of view, and absorbing and selectively re-emitting light.

The material chosen would be the simplest and most straightforward to produce the desired effect. Choosing the material does not determine the effect, rather the material is determined by the effect. Smart materials may simplify the system, but we are unlikely to encounter a need that can’t be met by conventional materials and technologies. A mechanical louver system will produce the same effect as electrochromic glazing, a pneumatic actuator assembly can produce the same results as shape memory alloys.
Conversely, just as the field of architecture has not understood smart materials as generic mapping mechanisms, the field has also not exploited the specific differences from material to material. Looking at just one behavior—the transmission of light through a transparent medium—we see that while there are several smart materials are capable of controlling transmission, there are nevertheless significant differences in how they do so, as well as in the specific results. The changes may be instantaneous or gradual, or they may occur in steps or bi-directionally. Smart glazing is often proposed as a seamless method for stabilizing light transmission to the interior as daylight levels on the exterior change, but there is no material that actually does this. Rather than assuming that there is a material out there that will fill a preordained application, one should be asking questions about how best to exploit the particular and unique characteristics of each material.

**Light as a Material Medium**

Consider the provision of light in a building. The only need for light in a building is for use by the human eye. The eye, however, intercepts but a tiny fraction of ambient light, while lighting systems are designed to fill the entire volume of a room with steady levels of light. At the beginning of the twentieth century, there was little understanding of how the eye functioned, and theories of electromagnetic radiation had yet to be applied to ambient light. Without theoretical underpinnings, lighting systems were ad hoc, determined from what one could observe, and standards grew from an empirical understanding of how the technology performed. There was no opportunity to do otherwise, with the result that, similar to HVAC technologies, lighting systems became increasingly disconnected from effect, instead producing repeatable ambient environments regardless of the occupants’ needs and the building’s specific characteristics.

This type of ambient system, while adequate for meeting the basic visual needs in a wide variety of buildings, requires enormous amounts of energy to maintain. Current knowledge of science and physiology challenge the need for this type of environment. Indeed, the provision for ambient lighting in a space requires substantially more light than is desirable for the eye. The human eye is highly sensitive to specific wavelengths in particular places across the retina. Furthermore, the quantity of light, which is the standard that drives lighting design, is irrelevant once minimum conditions are met. And these minimum conditions are generally one to two orders of magnitude lower than the amount of light that conventional systems supply. Functionality of the eye occurs primarily through highly selective contrasts, spectral as well as luminous, within the field of vision. None of the ambient lighting systems are capable of producing those contrasts. Many smart materials, however, are capable of these discrete manipulations, all of which take place at the micron scale.

Light emitting diodes (LEDs) represent a smart technology that could directly determine the visual response of the eye. Their discrete size and specific spectral bandwidth can be configured in a multitude of different arrays to create any visual image. They have been well employed for this purpose in the design of displays and screens, but they haven’t been well explored for creating three dimensional visual environments. They would be ideal for this application, however, as their highly selective behaviors come with low power and minimal infrastructure needs—as such they can be located anywhere to produce the desired behavior when and where it is useful, and only when and where it is useful. What LEDs cannot do very effectively is produce the ambient light of general illumination. Nevertheless, the field of architecture is committed to using LEDs as a substitute for conventional lighting in general illumination, even insofar as the best projections conclude that they will never be able to achieve the efficacy of fluorescents, and that revolutionary developments would have to take place before any energy savings would be possible. The true potential of LEDs for saving energy remains untapped.

**Conclusion**

We must ask different questions—rather than asking how we can incorporate smart materials into our existing systems, we should be asking what it is that they do that we haven’t been able to explore before. Each smart material or technology that we encounter will be highly specific in regard to particular phenomenological behaviors, giving us the unprecedented opportunity to match state of the art science with an up-to-date knowledge of human needs. We need to begin to question our unwieldy and non-specific building materials and technologies, and look for opportunities to decouple functions. The more discrete a system is, the more directly, and hence efficiently, it can act. Indeed, it is not even the materials themselves, but their underlying principles that we need to exploit in order to redefine approaches to sustainability. In essence we return to our earliest assumption about what is and is not energy conservative. But instead of smart materials representing the antithesis of the simple, sustainable solution, we should consider them as the tools that will allow our systems to become simpler.

So what do James Turrell and Robert Irwin have to do with sustainability and smart materials? Their work represents the type of thinking about phenomena and effect that should underpin our approach to designing human environments, regardless of whether it is the thermal, luminous or aural environment. What matters—and the only thing that matters—is the resulting human perception of that environment. Instead the field of architecture has maintained its focus on the systems for making the environment with an ever increasing emphasis on performance. As such, the field’s use of smart materials has been tautologically constrained to improving the efficiency of existing technologies when instead the field should be trying to improve the design of the human environment. Turrell and Irwin designed and continue to design human environments directly and discretely by leveraging physical phenomena with the most strategic of material means. Smart and simple.

![Fig. 7: Heat transfer at different scales](image-url)
Notes
2. Ibid. p. 127-128
3. The Ganz field effect results when luminous contrast in the field of view is diminished thereby eliminating shadows and thus depth perception. Snow blindness is a common manifestation of this effect. Anechoic chambers completely dampen sound vibrations.
4. Ibid. p. 131
5. The author had originally proposed that there were two categories of smart materials—(1) property changing materials and (2) energy exchanging materials. She shifted from a descriptive classification to a genetic (derived from origins) classification system based on thermodynamics in an article written for Architectural Record. This summation on the types and the discussion about behaviors is excerpted from that original article. See Michelle Addington, “For Smart Materials, Change is Good,” Architectural Record (09/2007)

Figures
All images courtesy of Michelle Addington

Biography
Prior to teaching at Yale, Ms. Addington taught at Harvard University for ten years and before that at Temple University and Philadelphia University. Her background includes work at NASA/Goddard Space Flight Center, where she developed structural data for composite materials and designed components for unmanned spacecraft. Ms. Addington then spent a decade as a process design and power plant engineer as well as a manufacturing supervisor at DuPont. After studying architecture, she was an architectural associate at a firm based in Philadelphia. She researches discrete systems and technology transfer, serving as an adviser on energy and sustainability for many organizations, including the Department of Energy and the AIA. Her chapters and articles on energy, environmental systems, lighting, and materials have appeared in many books and journals. She recently co-authored Smart Materials and Technologies for the Architecture and Design Professions.