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Aerospace Applications of Programmable Matter

Aerospace Applications of Programmable Matter

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Administrative Note

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Introduction

For the owners of a $100 million satellite—a TV broadcast satellite, for example—avoiding bankruptcy often depends on the spacecraft's continued good health until its scheduled replacement is in orbit. Unfortunately, numerous failure modes are possible, including blown fuses, failed sensors, and browned-out solar arrays. The common trait of most such failures is that they cannot be repaired from the ground. In addition, it is not typically possible to repurpose a spacecraft or its components for new services that no one foresaw at the time of manufacture. Either way, a new satellite is required. However, when sensors, filters, emitters, and photovoltaic solar panels are made of Programmable Matter smart materials, the solution to a component failure or new mission requirement might be as simple as a software update.

Other advantages of dynamic materials include advanced energy management and energy scavenging from a variety of sources. Smart materials can even create new defensive capabilities, such as chameleon-style camouflage, deflection of laser beams, and even outright invisibility.

If it becomes possible to change the properties of certain materials on demand, based on remotely triggered instructions, the benefits for spacecraft—both crewed and autonomous—will be considerable. This white paper—by no means an exhaustive reference—is intended to serve as a primer on the principles behind smart materials and their possible aerospace applications over the next 50 years.

Four Kinds of Atoms

All matter is made of atoms and derives its properties, in part, from the fact that atoms are discrete objects yet are so small and so close together that light waves cannot "see" them individually. By extension, neither can electric and magnetic fields. To a photon, or to a large electrical current, matter appears to be made up of continuous substances rather than discrete building blocks. This fact is critically important in understanding the optical, electrical, and even thermal properties of materials. Equally important are the discoveries of recent decades, showing at least four different kinds of "atoms" that meet this same general description.

NATURAL ATOMS

Natural atoms are the 92 elements of the periodic table. Actually there are more, but the rest have unstable nuclei that will eventually fly apart into smaller atoms and loose subatomic particles that can damage the materials around them. For engineering purposes, this makes them unreliable building blocks.

However, 92 building blocks allow for a staggering number of combinations, and all the materials with which we are familiar—natural ones like coal and diamonds, ancient ones like bronze and glass, and modern ones like silicon carbide and gallium arsenide—are merely "Tinkertoy" sculptures of these natural atoms.

QUANTUM DOTS

A quantum dot is a very small grouping of tightly confined electrons whose collective behavior resembles that of a natural atom. For this reason, quantum dots are sometimes known as "artificial atoms."

To describe how this trick is accomplished, it is first necessary to talk about electrons and how they behave. Most materials are either conductors, which permit the free flow of electrons, or insulators, which resist it. Semiconductors are insulators that are capable of conducting electrons above a certain threshold energy—a useful trick that makes integrated circuits and other electronics possible. The most familiar semiconductor is silicon, which is used to make the vast majority of microchips found in today's consumer and industrial electronics. Because silicon's native oxide, SiO2, is the main component of sand and rocks, it is readily available and relatively inexpensive. In addition, when melted, purified, and hardened into sheets, silicon dioxide serves as one of our familiar insulators and building materials: glass. Unlike most other semiconductors, silicon is also nontoxic.

The electrical properties of a semiconductor like silicon are of course fixed by the laws of physics. Atoms hold electrons in shells that increase in size, capacity, and potential energy the farther they are from the nucleus. "Valence" electrons are found in full (or nearly full) shells, where there are few empty spaces through which electrons can move. These electrons tend to stay at home, so their levels exhibit a large electrical resistance and do not permit electricity to flow. "Conduction" electrons are found in shells that are more than half-empty and have lots of open space, enabling electrons to travel freely through them and move easily from one atom to another. Between these layers is a "band gap" of forbidden energies. Here, there exist no electrons at all—ever.

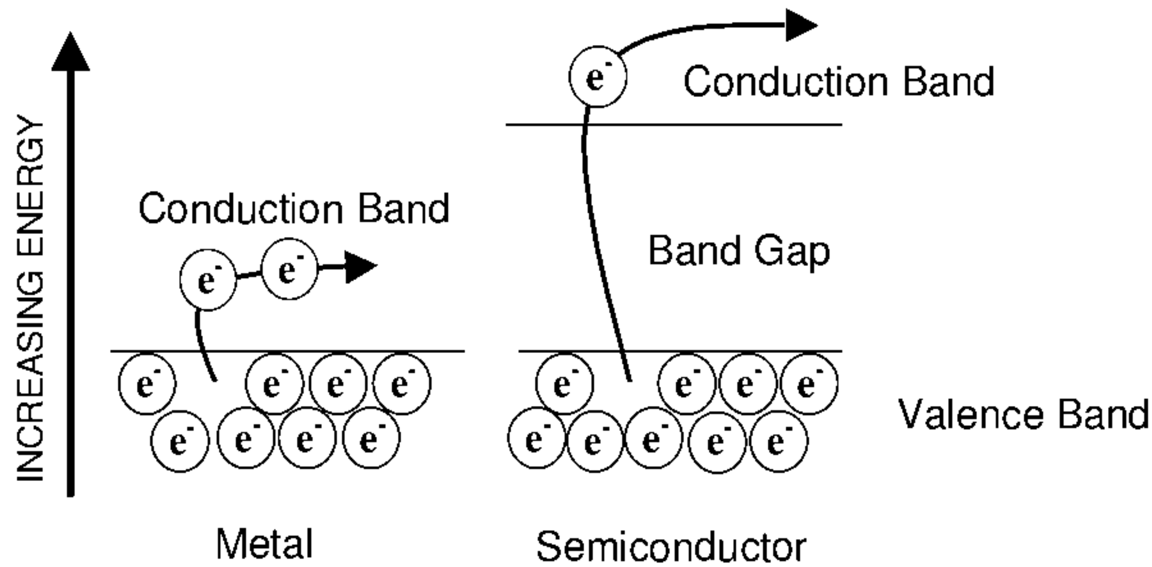

Figure 1. Energy Levels of a Metal and a Semiconductor. In a metal, many electrons reside in the conduction band and can be pushed to neighboring atoms with only a tiny addition of thermal or electrical energy. In a semiconductor, enough energy must first be added to excite the electron out of the valence band, across the band gap, and into the conduction band. Thus, to conduct electricity, semiconductors require much higher voltages and temperatures than do metals.

Electrons below the band gap of a semiconductor behave as though they were in an insulator, while electrons above the band gap behave as though they were in a conductor. They flow easily and can be used to store or transport energy and information.

The difference between a metal and an insulator is that the outermost electron shell of a metal atom is more than half-empty. It has lots of conduction electrons and lots of room for them to move around. An insulating material, such as sulfur, has an outer shell that is almost completely filled. All its electrons are valence electrons—homebodies that do not like to travel. Semiconductors have outer shells that are approximately half-filled. With the input of energy, their electrons can jump to a higher level where they find open space to travel through. Conduction electrons can also be "donated" by neighboring atoms.

A "quantum dot" is simply a very small structure—usually on the order of 5-20 nanometers—that contains a modest number of conduction electrons, which it confines in all three dimensions and prevents from leaving the structure. In addition, because the Heisenberg uncertainty principle requires position uncertainty to increase when particle momentum is restricted, the trapped electrons are unable to hold a well-defined position and instead behave as standing waves that resemble the orbitals of, and exhibit many of the same properties as, a natural atom.

However, there are two major differences between a quantum dot and a natural atom. First, there are far more than 92 possible configurations—an infinite number, in fact—for the confined electrons. Thus, with quantum dots it is possible to create designer atoms with properties that simply do not occur on the periodic table. If we want to, we can exert precise control over their optical, electrical, thermal, and magnetic properties rather than simply selecting these properties from the limited catalog nature has provided.

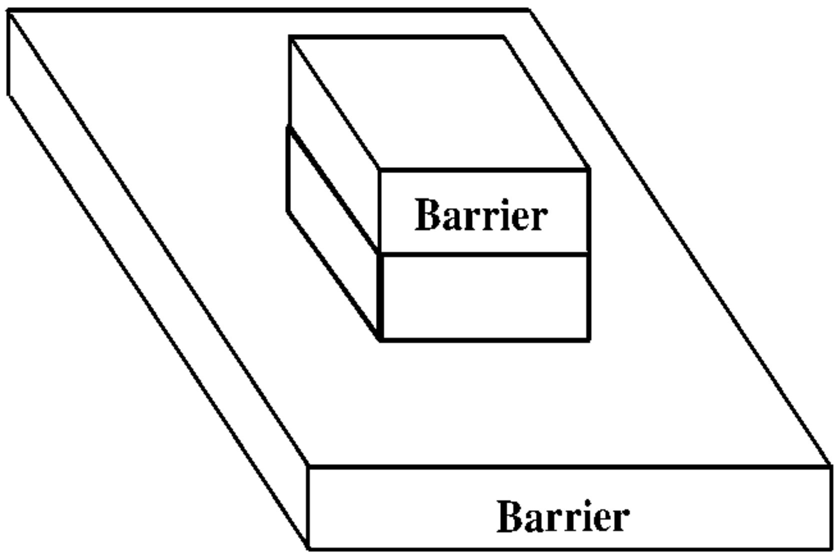

Figure 2. Quantum Dot. A quantum dot confines electrons in a very small volume of space, forcing them to behave as standing waves. Their structure thus resembles the electron clouds or "orbitals" of an atom.

Second, it is possible to pump electrons in and out of a quantum dot using electric fields. Thus, instead of a single designer material, it is possible to create a programmable material whose "atoms" can be changed on demand, allowing a bounded but infinite variety of material properties that can be summoned or dismissed at will.

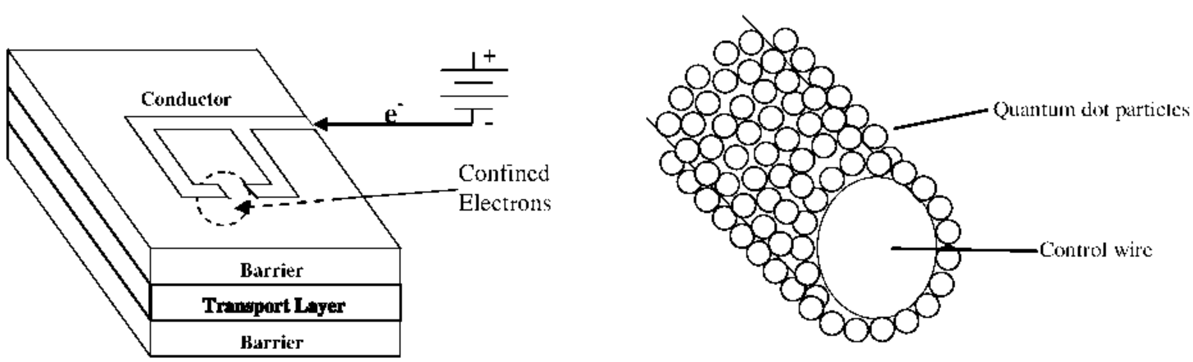

Figure 3. Programmable Materials. Various structures use electric fields to vary the confinement properties of quantum dots and can be assembled into bulk materials.

PHOTONICS AND METAMATERIALS

"Sub-wavelength" features are objects implanted on or embedded in a transparent material that are larger than atoms or molecules but smaller than a wavelength of light. They can have significant effects on the optical properties of the material, since they change the way it responds to electric and magnetic fields. However, because they are too small to be "seen" by the photons interacting with them, they do not directly block the passage of light. The result is a transparent material whose optical properties (permittivity, permeability, index of refraction, and coefficients of reflection, transmission, and absorption) do not necessarily match those of any natural material.

Photonic crystals exploit this principle by varying the density or refractive index of a material in a regular, periodic way. Just as light is affected by the spacing of atoms in a natural crystal, it can be affected by the (much larger) spacing of sub-wavelength features in a photonic crystal. Thus, photonic crystals can efficiently reflect some wavelengths of light while absorbing, transmitting, bending, or scattering others. This can be useful, for example, in telecommunications, where a single optical fiber may carry thousands of different signals. Because similar effects occur naturally in many gemstones (opal, for example), photonic crystals can also serve as artificial gems.

Whereas photonic crystals are generally insulators, another class of materials—called superlattices—is made from semiconductors, metals, and other substances stacked in very thin layers. Such materials "look" like crystals to the electrons and photons moving through them but can have properties that do not occur—or occur only weakly—in nature. Two examples are "magnetoresistive" materials made from alternating layers of iron and a nonmagnetic material such as chromium. Even in very tiny quantities, such materials can be used to sense magnetic fields with much greater sensitivity than can any natural material and are widely used in hard disk drives and digital compasses.

In a "metamaterial," the sub-wavelength features are conductive metals surrounded by a transparent dielectric material such as glass, air, or empty space. In much the same way a metal rod interacts with radio waves and can thus serve as an antenna, the "atoms" of a metamaterial create strong resonances at particular wavelengths that can have more profound effects on light than can any of the material systems described above. The best known of these is negative index of refraction, a property that allows materials to bend light "the wrong way" and thus defy the laws of classical optics.

LIQUID CRYSTALS

Although they were discovered in the late 19th century and have been used in video displays since the 1960s, liquid crystals can be thought of as an advanced 21st century technology that somehow fell backward in time. They are essentially a fourth state of matter, possessing some properties of a liquid and some of a crystalline solid. In addition, they are "birefringent," meaning they have a different index of refraction, depending on the angle or direction of light passing through them. They are capable of serving as photonic crystals, and under the influence of light, heat, electric and magnetic fields, and mechanical or chemical alignment layers, they can be rearranged at a moment's notice so that their optical properties are transformed.

Today, people are accustomed to thinking of liquid crystals as pixels in a video display. However, their capabilities extend far beyond this. With proper substrate design and the application of electric fields and other alignment or disalignment mechanisms, liquid crystals can be used to reversibly block, bend, focus, scatter, reflect, transmit, twist, polarize, diffuse, and absorb light in limitless combinations.

"Impossible" Materials

When natural materials are shaped and combined in macroscopic ways, it becomes possible to produce what Roger Bacon described as "natural magic": devices such as mirrors, lenses, polarizers, magnets, wires, semiconductors, fluorescent dyes, and phosphorescent screens that glow in the dark. We take these devices for granted, but to our primitive ancestors they would have seemed supernatural, as indeed they are in the sense of not occurring naturally.

However, by combining the same materials in nanostructured ways, we achieve a higher order of magic: Bragg mirrors that reflect a single wavelength while transmitting all others, superlenses that defy Newton's diffraction limit to focus with unnatural sharpness, superstrong magnets that measure the world around them with unprecedented sensitivity, photoluminescent materials that absorb light in a broad range of wavelengths and re-emit it in a single brilliant color. Soon we may have high-temperature superconductors and even materials that are functionally invisible.

One such "impossible" material hypothesized is the nanostructured "metapolarizer." Where classical polarizers either reflect or absorb half the light that hits them (typically resulting in energy wastage of 50 percent or higher), a metapolarizer simply ignores one polarity of light and converts or rotates or "retards" the other. This principle can be harnessed, for example, to double the battery life of a laptop display or to double the brightness of a flat-screen TV.

However, even these magical materials are "static"; that is, their properties are fixed at the time of manufacture. The greatest revolution in materials science may in fact come from materials capable of changing their properties on demand.

Advantages of Dynamic Materials

Leaving behind the world of static materials, we come to a sort of programmable magic whose fruits already include switchable mirrors, dynamic optical filters, deformable lenses, magnets and polarizers that appear and disappear on command. Less glamorous but equally important are such "behind the scenes" capabilities as tunable electrical conductivity, tunable bandgap semiconductors, tunable lasers, and tunable photonic crystals.

However, the ultimate exemplar of designer materials will be multifunctional smart materials, which are capable not only of switching a particular property on and off but of changing their properties—indeed, their very purpose—on demand.

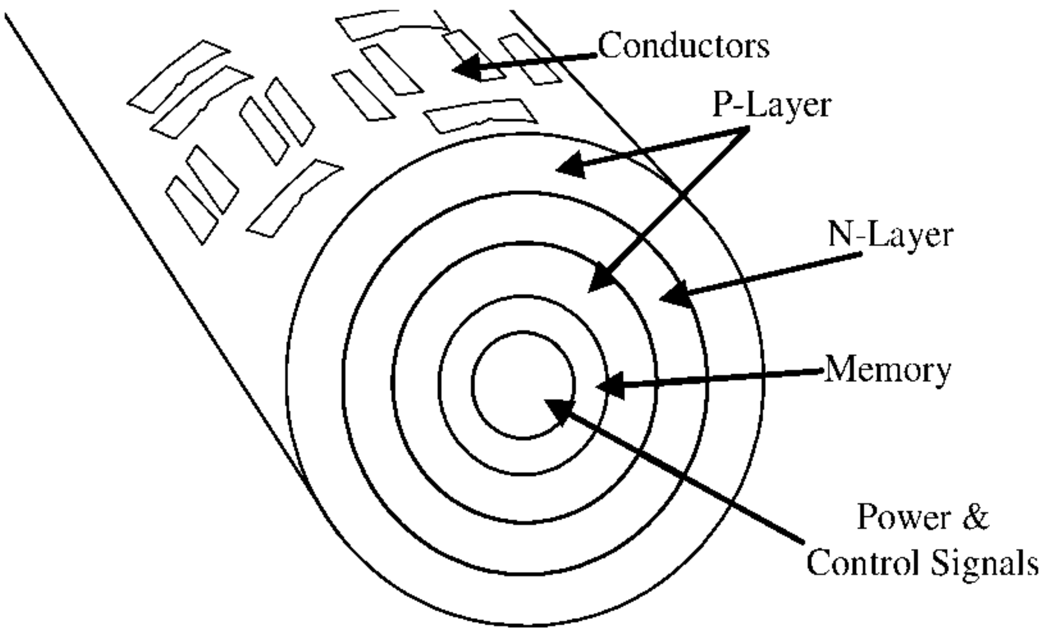

Figure 4. Wellstone Fiber. A notional "Wellstone" fiber uses careful arrangements of conductors, semiconductors, and insulators to produce a long, flexible cylinder whose surface is studded with artificial atoms. When woven together, these fibers create a bulk material whose properties are programmable via external signals.

In the future, advanced supercomputers may be able to monitor the objects around us—our desks, our countertops, our walls and windows and chairs—and modify their properties to suit the needs of the moment. Transparent or opaque? Reflective or absorptive? Conductive or insulating? Magnetic? Flexible? Luminous?

In theory, a block of true Programmable Matter should be able to select any point on any of these axes at any time. Other effects may be desired as well, including magnetoresistivity, photo-/thermo-/piezoelectric effects, superconductivity, and the ability to perform computations (a truly "smart" smart material).

Unfortunately, many of these traits are strongly correlated, so that, for example, a material that managed to be both electrically conductive and thermally insulative probably could not be made transparent as well. A computer is unlikely to double as an air conditioner. Still, the possible combinations—the number of things we could actually do—would be much larger than the (already vast) range of natural material combinations.

Although the smart matter of 2050 will probably be operated electrically, electrical operation presents a number of challenges today. First, the required nanostructures are very small and intricate, with manufacturing tolerances that push or exceed the limits of current technology. Second, the control wires, electrodes, and other conductors in such devices mean they will likely be vulnerable to electromagnetic interference. Like a pocket calculator in a microwave oven, programmable materials face a harsh electromagnetic environment and will need to be shielded and safeguarded against spurious behavior. In addition, there is the threat of hackers. As our society turns over the control of more and more infrastructure to computers, we add not only new strengths but also new vulnerabilities. We must be extremely cautious about handing malicious hackers the keys to matter itself!

The greatest challenge, however, is temperature. The resistance of an electrical wire varies with temperature, and while we scarcely notice the difference with the fat copper wiring in our houses, the delicate films and nanowires of Programmable Matter smart materials feel it very strongly. Other critical properties, such as the bandgaps of semiconductors, the optical spacing of photonic crystals, and the internal symmetries of liquid crystals, are also temperature sensitive and must be managed carefully to avoid overwhelming the control signals passing through the material.

Early attempts at programmable quantum dot materials were so temperature sensitive that researchers found that altering temperature, rather than the electric field, was actually the easiest way to control the response of the materials. In fact, by selecting materials with higher temperature sensitivity, we were able to enhance these effects to produce thermally activated smart materials with no need for electric controls at all.

Of course, materials that respond to temperature are not new. Thermochromic (color-changing) liquid-crystal thermometers are well known, and in the mid-1990s, Chinese researchers developed a thermochromic paint that turns a cool-blue shade when warm, a warm-red shade when cool, and pale green at room temperature. This was done mainly for thermal regulation—the paint allegedly could increase the temperature of a building by about 4ºC in winter and decrease it by about 8ºC in summer—although the researchers also claimed an aesthetic benefit to having a home's color match the season. Even more impressive effects could be achieved if black and white (or clear and silver) were available color choices.

Although thermochromic building materials were very rare until recently, a number of other mechanisms—including electrochromics, photochromics, and automatic mechanical blinds—have been used to create "dynamic windows" that actively control solar heat gain in buildings and display many of the properties (if not the principles) of a true smart material. Buildings account for 40 percent of all energy consumed in the United States, including 71 percent of all electricity and 38 percent of all carbon dioxide emissions. Managing solar heat gain and controlling the building's thermal envelope are the most effective ways of reducing energy use. The same principles apply, of course, to spacecraft, for which solar heat is even more intense and nighttime (in the shadow of the Earth) is colder.

In 2003, the U.S. Department of Energy's Lawrence Berkeley National Laboratory (LBNL), on behalf of the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE), performed a study focused on dynamic window systems capable of darkening or shading automatically such that the solar heat gain coefficient (SHGC) varied between 0.26 and 0.40. Analyses were performed for eight U.S. cities: Boston, Denver, Jacksonville, Kansas City, Phoenix, Sacramento, Seattle, and Washington, D.C.

The ASHRAE study found that across all eight climate zones, buildings with low-emissivity ("low-E") glass saved an average of 8-15 percent on their total annual energy (heating, cooling, and ventilation) costs, whereas the addition of dynamic window systems saved an additional 6-19 percent. In other words, the savings associated with a dynamic window are approximately as large as the savings associated with low-E. Furthermore, because dynamic windows and low-E coatings save energy through completely different mechanisms, their effects are complementary and, thus, their savings can be combined. In addition, while low-E glass reduced peak cooling loads by 2-14 percent, the dynamic windows provided an additional 5-38 percent reduction in peak cooling load, allowing significant downsizing of the building's air conditioning system.

The report concluded that dynamic windows "offer the potential for significantly greater HVAC savings than can be achieved with currently available high-performance windows," have "much lower energy costs than static windows," and "provide the best of all worlds."

Early Commercialization of Smart Materials

In the third quarter of 2009, RavenBrick LLC introduced RavenWindow, an "active-passive thermoreflective" window film that is transparent when cold and partially reflective when hot. The dual-purpose smart film is intended to manage and harness solar heat gain in windows. The film costs much less than do existing smart window technologies and offers superior energy savings.

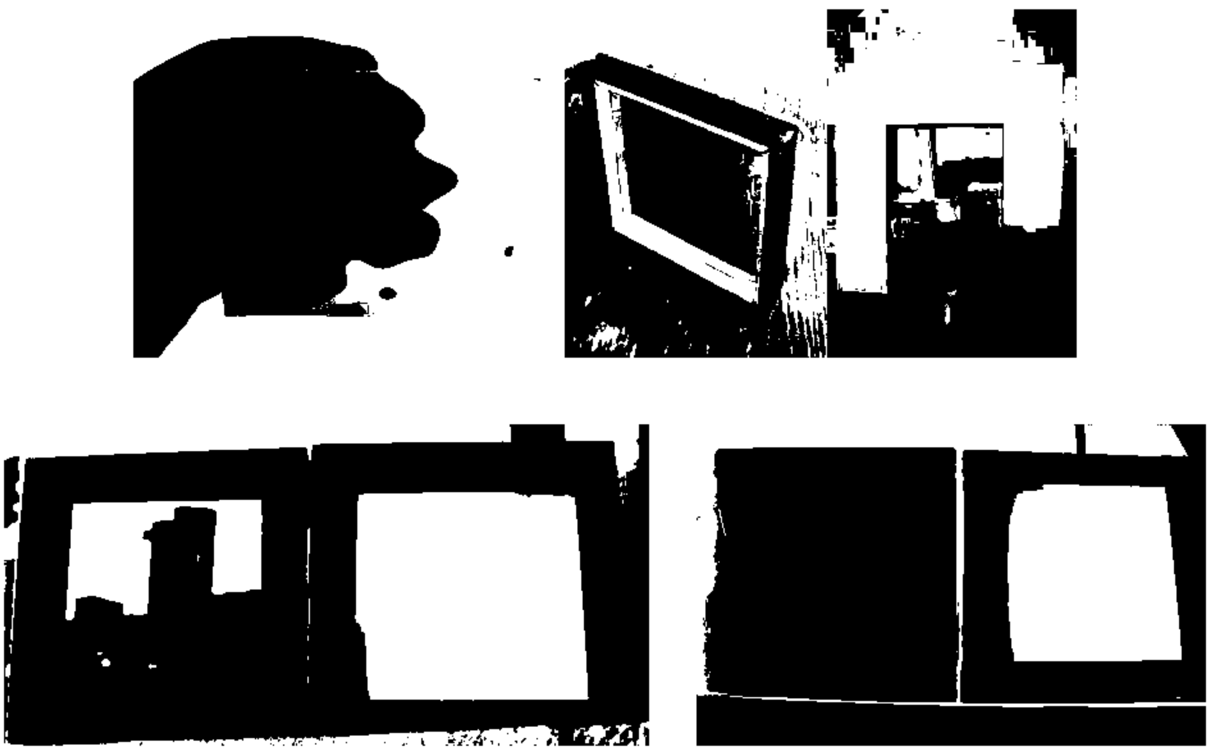

Figure 5. Assorted Views of RavenWindow and RavenLight Filters in the Cold (Transparent) and Hot (Reflective) State.

RavenWindow film is transparent when cold and partially reflective when hot, allowing an SHGC range between 0.12 and 0.43—more than twice the range studied by LBNL. Studies performed by RavenBrick using LBNL tools show energy savings up to three times those of low-E glass alone.

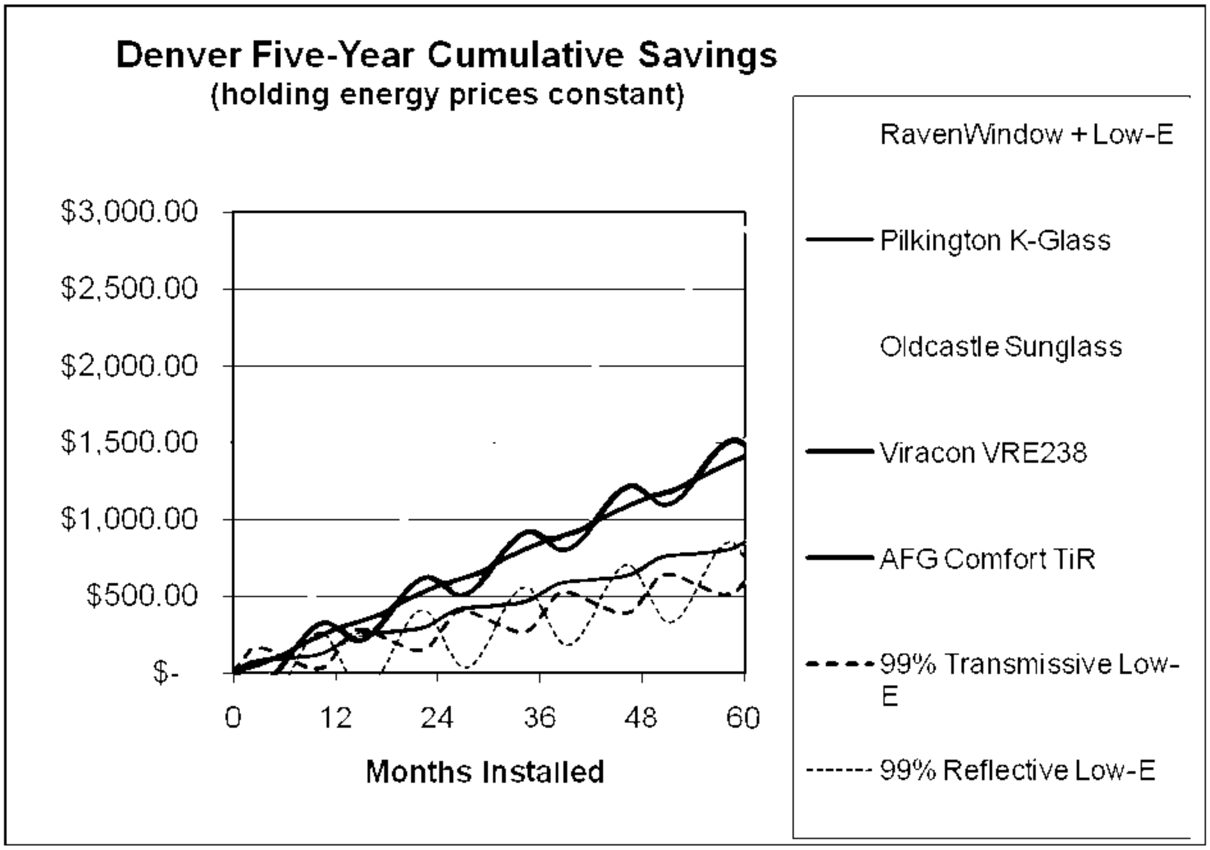

Figure 6. RavenWindow Smart Window Film Performance vs. Leading Incumbent Window Filters.

Assuming a retail cost of $25 per square foot, for large buildings across multiple climate zones, the payback period is 5-10 years. Even faster return on investment is possible if the retail cost can be reduced, which seems likely given the relative simplicity of the technology. The payback period does not include capital cost reduction on HVAC systems, reduction in the cost of window coverings, and the tax and building permit savings associated with Leadership in Energy Efficient Design (LEED) certification.

Thermal Management of Spacecraft

The three laws of thermodynamics, in their simplest form, are (1) you cannot win, (2) you cannot break even, and (3) you cannot quit the game. Energy is never free, and nanostructured dynamic materials are of course subject to the same laws as natural materials. However, while energy can neither be created nor be destroyed, it can be moved around, changed in form, and also stored. Thus, for thermal management of spacecraft, dynamic materials have much more to offer than simply regulating solar heat gain.

One example is active heat transport. A Peltier junction is a solid-state heat pump made from two dissimilar semiconductors. When a current is passed through the junction, one face grows hot while the other grows cold.

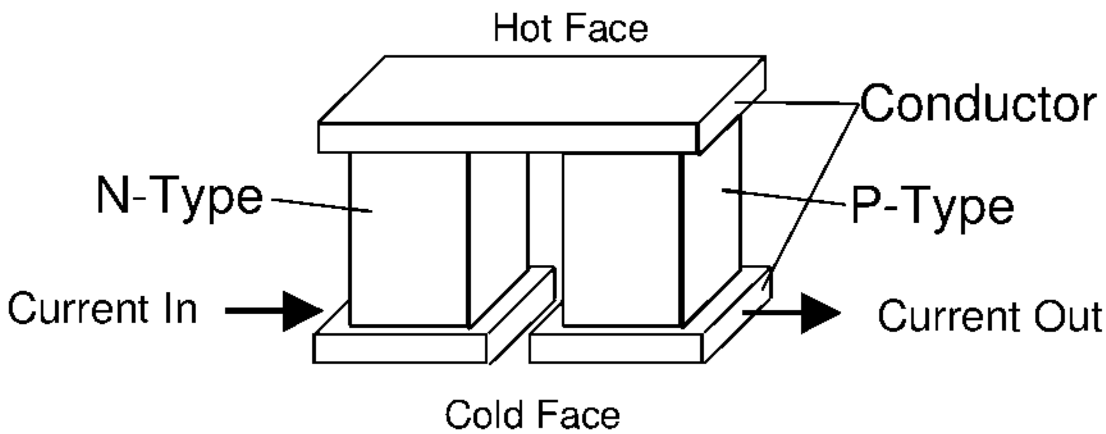

Figure 7. Peltier Junction Heat Pump. Running an electrical current through this device will drive thermal energy into the upper conductor, which grows hot. The lower conductors lose energy and become cold. The same principle works in reverse: heating the top conductor (or cooling the bottom one) will create an electrical voltage across the device.

Unfortunately, natural materials are relatively poor at this—the best efficiencies achieved with them so far are around 10 percent. An optimal thermoelectric material would be simultaneously a strong electrical conductor—perhaps even a superconductor—and an excellent thermal insulator.

Fortunately, in 2001, scientists at the Research Triangle Institute in North Carolina used semiconductor superlattices to create a Peltier junction that operated at 2.5 times the efficiency and 23,000 times the speed of all previous designs. The electrically semiconductive superlattice materials were unusually good radiators—and unusually poor conductors—of heat.

For spacecraft hulls fashioned from programmable materials, it should be possible to create Peltier coolers on any surface in order to pump heat out of one area and divert it to another. In addition, it may be desirable to manipulate the thermal conductivity of the spacecraft skin—highly conductive in some areas, highly insulating in others—either to smooth out temperature differences between the sunward and shadowed sides of the spacecraft or, in some cases, to accentuate them (for example, so that a radiator, precision blackbody, or cryogenic instrument on the shadowed side remains as cold as possible).

Finally, it may be desirable to store heat for later release. This can be accomplished, for example, by placing an insulating barrier around a hot portion of the spacecraft skin while also reducing the emissivity of the hot spot so its ability to radiate the heat away into space is minimized. Later, the hot spot can be reconnected to the rest of the spacecraft skin through conductive bridges, allowing the heat to escape and spread out.

In addition, thermal management of the spacecraft interior will provide significant benefits for the overall energy budget. The table below details the energy consumption of a typical household (a reasonable analog for a crewed spacecraft, with the exception of energy required for air circulation and other life support functions).

Table 1. Daily Household Energy Consumption (USA, 1993-1997)

Space Heating	41 kWh
Water Heating	15 kWh
Refrigeration	7 kWh
Space Cooling (air conditioner)	3 kWh
Lighting	3 kWh
Clothes Drying	2 kWh
Cooking	1 kWh
Dishwashing	1 kWh
Other Appliances (TV, stereo, computer, etc.)	7 kWh

Over 80 percent of the energy budget is spent heating and cooling things—often at the same time. It is clearly desirable to recapture the waste heat from cooling operations and divert it to subsystems, such as the water heater.

Energy-Scavenging Spacecraft Skins

Programmable materials can also be used to harvest, store, and redirect other forms of energy. Spacecraft are constantly bathed in a very high solar energy flux and experience sharp temperature gradients, as well as periodic changes in magnetic and electric field. All of these represent possible energy sources that can be scavenged from the environment without disrupting other spacecraft operations.

The photoelectric effect occurs when photons strike a material such as a semiconductor or metal. The energy of the photons is absorbed by the electron shells of atoms, and as a result, some electrons may shift from the valence band to the higher, looser energies of the conduction band. This is the source of the voltage in photovoltaic cells and allows the direct conversion of light energy into electricity. This effect generates electron-hole pairs (that is, knocks electrons off their parent atoms) in a material such as silicon, and if the electrons are forced to go in one direction and the holes in the other, then an electrical voltage is generated.

Today's commercial solar cells are around 13-percent efficient at converting sunlight into electricity, which makes them economically marginal for use on Earth in any but the sunniest climates. Even NASA's most sophisticated—and expensive—solar cells are usually no more than 24-percent efficient, although experimental multilayered designs have achieved upwards of 40-percent efficiency in the laboratory. (Notably, such converters once blurred the lines between a designer material and a collection of nanoscale devices.)

These efficiency numbers reflect a practical limit, not a theoretical one. The available materials—primarily silicon and other semiconductors—are simply not very photoelectric, and the junctions we can place in them are not very efficient electron-hole separators. With natural atoms, the choices are quite limited. However, with artificial atoms and designer materials of various types, and particularly programmable materials that can adjust to changing conditions, much higher efficiencies are possible. Clearly, it is very desirable for the sunward face of a spacecraft to be as photovoltaic as possible.

In addition, sharp temperature discontinuities can be an energy source. A Peltier junction can be run in reverse so that heating one side of it and cooling the other produces a voltage. This seems quite straightforward at the sunlight terminator of a spacecraft—the line dividing the sunward and shadowed faces. Here, although there exists very little direct solar energy, the temperature gradient can be quite steep, indicating a potentially quite large amount of harvestable energy that would otherwise go to waste.

Still another way to harvest energy is through the piezoelectric effect—a voltage generated when certain materials are under pressure. Because the atmosphere within the spacecraft exerts a constant outward pressure on the hull, this seems a good candidate for energy scavenging as well. In addition, for areas of the spacecraft interior that are expected to receive intermittent pressure (for example, because crew members bump up against them), this energy can be harvested as well. The total energy of these interactions may not be very large, but for programmable materials that would otherwise be sitting idle, energy scavenging is an excellent activity even at very low efficiency.

Smart materials can also be used to store the energy they generate. A capacitor is simply a pair of conductors with an insulator between them, which can separate charges under the influence of a voltage, sending electrons to one side and holes to the other. This separation of charges, like the separation of chemical ions in a battery, stores energy. Automotive ultracapacitors have a bright future, and replacing their "holey carbon" with nanostructured programmable materials may allow storage of even more concentrated charges.

Superconducting loop batteries are another possible storage mechanism, particularly on the shadowed side of the spacecraft, where cryogenic temperatures are easily achieved.

Advanced Concepts in Programmable Materials

Programmable materials can assume novel, unnatural configurations, but their primary advantage is that their properties can be changed on demand. Thus, it becomes possible, for example, to reconfigure a single spacecraft attitude sensor to operate as a sun sensor, horizon sensor, or star sensor, as required. The same technology can convert any black-and-white imaging sensor into a multispectral sensor—at low cost and with no moving parts. In fact, a single device could be a receiver for optical or infrared signals, a tunable optical or infrared filter, or a precision light source for calibrating other sensors. In addition, when not in use, the device can serve as a photovoltaic cell, converting sunlight into additional electricity.

In fact, the inherent re-programmability of the material properties means devices incorporating dynamic materials can be adapted to novel purposes that were not anticipated at the time of manufacture. In the future, dynamic materials may serve in such applications as polarizers, magnetic and electric field sensors, and color-changing solar sail controllers for station keeping. This open-ended flexibility has the potential to dramatically improve the value and performance of spacecraft that lie beyond our current capabilities.

Quantum computing is another possibility. Qbits were first demonstrated in 1995 by the National Institute of Standards and Technology in Boulder, Colorado, and by the California Institute of Technology in Pasadena. Because computing power increases exponentially with the number of qbits (versus linearly with the number of binary bits), a 64-qbit computer is roughly 18 billion billion times as powerful as a 64-bit binary one. In a quantum, programmable world, the concept of "operations per second" as a computing bottleneck may simply vanish.

Opinions vary widely on how smart or intelligent or conscious a machine can ever be, but as IBM's chess champion Deep Blue demonstrates, even a stupid machine can appear brilliant if it runs fast enough. This is known in industry as "weak AI," but with the power of quantum computing behind it, the results could in fact be extremely powerful.

Scenario for Possible Applications

Imagine a space station in low-Earth orbit. It is in darkness, its running lights blinking, but as it clears the terminator and swings around into full sunlight, we can see that its surface is one big, dead-black solar collector. Its exterior drinks in sunlight, taking some of it as stored heat and pumping the rest into electrical wires, which shuffle it off into a bank of capacitors. If we could see through the hull, we could watch the capacitors swelling—literally growing larger as more energy becomes available and more of the station's mass is allocated to storing it.

But we cannot see through the hull, there are no windows, and the station would be completely dark inside if not for dim little nightlights glowing here and there, lighting the way in case someone visits the galley in search of a nighttime snack. Beneath its layer of solar collectors, the hull is one big, opaque insulator, keeping the cold, bright "morning" of outer space at bay.

Then, suddenly, the clock strikes 0600 Houston time, and an arrangement of diffusive portholes and mirrors gradually fades into existence, waking each of the station's inhabitants with the gentle morning sunlight. These fenestrations are not stationary; they crawl across the walls as the station moves in its orbit and changes its orientation to the sun. Greeted by the soft voice of the station's central computer, our astronauts awaken.

While the astronauts eat their breakfast in a bright little galley, more portholes appear, looking down at Earth and at points of interest in the black sky above it. However, the crew's comfort and privacy are not compromised; through the mirrored glass, ground-based and space-based telescopes cannot see inside the station, and the amount of reflectivity is constantly controlled, balancing the needs of daylighting, solar heat gain, and the aesthetics of a good view. In a pinch, the station can even turn "invisible," taking light and heat from one side and emitting a matching signal on the other side.

After breakfast, some of the crew settle into office niches to check their email, voice, and video messages. Almost any surface in the station can serve as a desk, keyboard, computer screen, video camera, or drafting table. Others proceed to scientific experiments and routine maintenance activities throughout the station. Portholes and skylights follow them around, but now they are looking out mainly from the station's shady side, avoiding direct sunlight. The station has absorbed and stored all the heat and electricity it will need to get through the orbital "night" of Earth's shadow and is becoming stingy about accepting more energy.

Soon, the station has converted almost its entire exterior into a mirror, keeping only a small solar collector for maintenance voltage and a few shaded portholes for light and aesthetics. The central computer idly browses its library and encyclopedia and the Internet, finding news, entertainment, and educational material it knows the astronauts will want to see. With the power of quantum computing, it is even able to analyze this information.

Halfway through its hour-long orbital "day," despite every precaution, the station is in danger of becoming too hot. Peltier junctions begin to appear in the hull, their radiators—colored black and yellow and covered in HOT SURFACE warnings—swelling on the station's shadowed side. At the same time, a solar storm—predicted days ago—finally begins to kick up. The hull compensates by generating a strong magnetic field to deflect the charged particles. This could be troublesome to the people and equipment inside the station, but the fields are deflected outside by sheets of superconducting material, cooled by still more Peltier junctions. The shields are up; the station is circling the Earth in its own little magnetic bubble.

Soon enough, though, the station's orbit carries it back into the planet's shadow. Sunset is brief and spectacular; the solar heat and solar wind vanish. Now the station is living on stored charge and stored heat. Windows look down on Earth—a warm object that radiates brightly in the infrared—but not in the cold vacuum of space. The hull becomes thermally conductive for a few seconds to ease any temperature imbalances that have developed and then switches to an insulative, low-emissivity mode to conserve heat.

Now the astronauts are followed around by electroluminescent task lighting. The station seems to relax and to take things a little slower until "dawn" breaks again and the cycle repeats itself.

Hours later, the crew dines in the same galley where they breakfasted. As the sun sets, the station's interior lights come up dimmer than before. This is the astronauts' cue to begin getting ready for bed, so after a bit of conversation, they shuffle off to their respective cabins. At 2130 Houston time, the lights and portholes slide into an even dimmer setting, and the crew drifts off to sleep.

Directions for Future Research

Although the aerospace industry has traditionally been a source of spinoff technologies that are later adopted by consumers, in recent years the reverse trend has been equally prevalent. For example, although GPS technology was developed by and for the military, and integrated circuits were developed for the Apollo lunar missions, today the military often employs low-cost civilian GPS receivers, and Space Shuttle astronauts use laptop computers made for home and office use. This makes economic sense, as mass production for large consumer markets offers not only economies of scale but also vast potential for user feedback, design iteration, and direct measurement of the popularity (and, indirectly, the usefulness) of different designs. Thus, consumer products may be both cheaper than, and of superior quality to, those produced by the aerospace industry.

Assuming this trend holds true across the next four decades and applies even to exotic technologies such as programmable materials, it is logical to suppose that consumer applications such as smart windows and multispectral night-vision sensors are more likely to spin off to the aerospace industry than the reverse. Therefore, advancement of smart materials technology for aerospace applications will likely depend on research and development for consumer applications. In addition, the "low-hanging fruit" applications, with the largest markets and thus the highest profit potential, will have the greatest accelerant effect on the technology.

Therefore, near-term applications such as smart windows and energy-saving metapolarizers, which offer direct and immediate economic advantages (namely energy savings) and which dovetail neatly with existing infrastructure, should be considered the most promising for research over the next 5 years.

Over the longer term, a number of problems must be overcome for fully programmable material devices to be constructed. In the case of metamaterials, the primary challenge is fabrication. Numerous nanopatterning techniques have been developed for producing regular patterns on a surface, including grids, gratings, and patterns of dots or holes. However, the resonant properties of metamaterials typically require more complex structures that are not easily mass produced on the scales necessary for optical wavelengths—typically 100 nanometers or less, and often as little as 10 nanometers. Promising candidate technologies include nanoindentation lithography, extreme ultraviolet photolithography, and photolithography using metamaterials-based "superlenses." Liquid crystal technology is more mature, but to survive in the harsh environment of outer space, it may need to evolve higher resistance to ultraviolet and other forms of ionizing radiation.

Perhaps the most promising long-term technology is the addressable quantum dot array. However, for broadly programmable applications—particularly in aerospace—the issue of temperature sensitivity must be brought under control. This may involve direct temperature control of the active surfaces or development of high-bandgap material systems for which the coefficient of thermal expansion and bandgap versus temperature slope are both small. In addition, shielding the metallic nanostructures against interference from stray electric or magnetic fields will be very important and may rely on as-yet-undeveloped techniques or materials (for example, high-temperature superconductors).

However, the vast potential of programmable materials and devices, as well as the clear advantages they hold in certain earthly and aerospace applications where traditional material limitations clearly constrain functionality, should not be underestimated. Building and vehicle skins, sensors, and windows are three areas that particularly lend themselves to enhancement with multifunctional materials, and the commercial advantages of developing these will be considerable. As with transistors, LEDs, LCDs, integrated circuits and other late 20th century technologies, the economic imperatives are likely to overcome many significant technological barriers, and by 2050 it seems likely that our grandchildren will have difficulty imagining a world where these objects are made from traditional, inert materials. Their relationship to material objects may be analogous to our present-day relationships with electronic graphs, data files, and web pages and documents. We think nothing of "tweaking" these over and over again in a way that we could not if they were simply printed on paper; indeed, we expect such files to be "living documents" that change as frequently as the world around them changes. Most of us would have a difficult time adapting to the technology of even 30 years ago.

Finally, with any emerging technology, the number and scope of "unknown unknowns" may be considerable. Some things that appear easy now may in fact turn out to be extremely difficult. Conversely, many seemingly daunting problems turn out to have remarkably simple solutions. Indeed, the problems faced by—and solved by!—advanced programmable materials in 2050 may be impossible to forecast today with any accuracy or confidence. Rather, we must roll up our sleeves and begin experimenting.

Conclusions

Many elements of the preceding scenario are based on current and emerging technologies; others are speculative. However, if even a fraction of these possibilities were to become reality in crewed and crewless spacecraft, the gains in energy efficiency, mass reduction, safety, comfort, and mission flexibility could be extremely significant and well worth pursuing. All that is needed is a commitment to develop the underlying technologies.

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