The Internet of Materials: A Vision for Computational Materials

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"The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it."

Mark Weiser's words in 1991 inspired a generation of researchers to explore an "off the desktop" world of ubiquitous computing.[1] Revisiting his vision of the "Computer for the 21st Century" is timely, now that we are firmly in the 21st century and many of his ideas have borne fruit. A closer reading of the second sentence, initially intended to be interpreted metaphorically, contains an intriguing literal suggestion in the context of our technological world of 2020. A related vision from the late 1990s is that of "smart dust,"[2] in which extreme miniaturization would allow for floating or otherwise embedded wireless sensing throughout the physical world.

Advances in materials science and manufacturing today signal a time when we really will be able to manufacture new everyday materials that have computational capabilities "woven" into them, or wireless sensors that are either so small they are imperceptible or look and feel like the materials into which they are embedded. We are at the precipice of the age of the Internet of Materials (IoM).

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Rather than today's Internet of Things—a 20-year old concept that arguably is not really about everyday "things" at all but devices that have wireless connectivity added—the IoM really is about everyday objects made of everyday materials with the ability to behave as connected computational entities. I call these new and functional materials *computational materials*.

Weiser and his contemporaries pushed us to think about the blurring distinction between what is physical and what is digital. Barcodes, QR codes, and RFID technologies have allowed us to quickly connect a physical object to digital representations of that object. Indeed, some forecast that our future world will become increasingly hybrid in this physical–digital way.[3] Computational materials push us to think about a world in which the physical and digital are inextricably linked, with all of the potential opportunities and concerns that inspires.

There are three dimensions that clarify this vision of computational materials and IoM. In a world where everyday objects are computational, trillions and quadrillions of independent objects will cover a majority of the surfaces that surround us. Therefore, we have to emphasize the following three things.

Power

Everyone who designs mobile computing devices knows that the dominant constraint is power. These designers have to consider how much space is needed to provide a rechargeable or replaceable battery that has the capacity to power the device for a minimum tolerable period. In addition, when each of us has a dozen or so of these mobile devices, we can manage plugging them in or recharging them, as bothersome as that may be. In a world full of computational materials, we (individuals or organizations) will own or interact with millions of these items, making it impossible to manage from a power perspective. Therefore, *we have to strive for self-sustainable computational materials, ones that can harvest sufficient energy to carry out their computational function.*

Scale

Weiser predicted that the third generation of computing would result in individuals regularly interacting with many computing devices, but was he (or any of us) thinking seriously about how many, or how we would manufacture and deploy them? Despite the tremendous progress in cost savings predicted by Moore's Law, the number of integrated circuits (ICs) produced globally pales in comparison to other things we manufacture today. And, the cost of those ICs is relatively high. A single transistor today costs about $\$(5 \times 10^{-8})$.[4] While that may seem miniscule, imagine we wanted to add a sensing capability to road pavement in order to track traffic patterns. There are about $\$(1.23 \times 10^{8})$ square miles of paved roads in the world. Even if it took only 100 computing devices (e.g., transistors) per square foot to provide this sensing (and communicating) capability, that would cost over $170 billion. And, that is only for raw materials. Consider doing this for sidewalks and floor surfaces of public buildings, and it soon becomes clear that the costs are too high. Therefore, *we need to consider alternative paths to manufacturing computational materials in order to drive down their cost.*

Form Factor

Anyone reading this article can easily pick out a computing device from a collection of everyday objects. They just look distinctive. Computers do not look like a cup, a piece of paper, or a chair. If computational materials are to proliferate in our physical world, they must look more like everyday objects. Therefore, *we must produce computational materials that either look and feel like everyday objects, or, when placed on everyday objects, do not alter the look and feel of those objects.*

By combining advances in materials, manufacturing, computing, and design, we can directly address these three challenges. But this all begs the question: even though we are moving in the direction of creating large-scale, cheap, and self-sustainable computational materials, why would we want them? After I show some examples of computational materials developed at Georgia Tech, I will address the more serious questions of why we might want computational materials and the IoM, as well as additional important research challenges.

COMPUTATIONAL MATERIALS DEFINED

Computational materials are manufacturable materials that can acquire the energy through harvesting or wireless power transfer to do what today's computational devices can do. Specifically, computational materials should do some combination of *computing* logical operations, *storing* information persistently, *sensing* phenomena from the physical world, *actuating* to create perceptible changes in the physical world, and *communicating* to other computational materials. In addition, these computational materials are to be *manufactured cheaply* and at large scale so that they can be deployed *to support interesting capabilities for humans in the physical world*.

Figure 1 depicts four computational materials projects at Georgia Tech.

Saturn

SATURN (Self-powered Audio Triboelectric Ultrathin Rollable Nanogenerator) is an early example of a computational material that can sense vibration, such as sound.[5] SATURN can be manufactured from inexpensive components, is flexible so that it can be integrated into many different surfaces, and powers itself through the

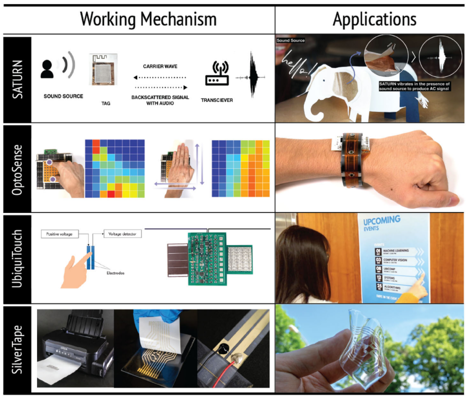

Figure 1. Four projects exploring computational materials at Georgia Tech. The left column shows technology details, and the right shows and application scenario. All examples except for OptoSense have been published.

sound or vibration it is sensing. The concept of a triboelectric nanogenerator is fairly general and intriguing, and we have demonstrated its use in a waterproof silicone-based cord form factor as well.[6] Coupled with passive wireless communication using radio frequency (RF) backscatter, these self-sustaining sensors can also communicate data to traditional computing platforms, opening up a wide variety of application opportunities.[7]

OptoSense

OptoSense is a self-powered sensing platform which harvests energy from ambient light and also senses the fluctuating patterns of ambient light on various arrangements of photodiodes to infer user activities and interactions at the surface level on everyday objects. As a single photodiode, it can detect the opening and closing of doors, drawers, and bottles. In a one-dimensional (1-D) array, it can detect fluid levels and perform crude content determination, or when around a wrist can count steps as an individual walks. In a 2-D array, it can detect hovering and multitouch gestures or detect the presence of a human body as it passes by. The initial OptoSense prototype platform uses traditional low-power silicon-based photodetectors (see Figure 1), but we can replace those photodetectors with organic semiconductors, which offer a path toward thinner, conformable form factors that are amenable to mass manufacturing processes that drive down the cost.

UbiquiTouch

UbiquiTouch is an example of an ultralow power wireless touch interface that leverages both inexpensive printed electronics and RF backscatter.[8] Like OptoSense, it uses a low-power detection system, this time conductive patches printed onto a flexible substrate. It detects human touch and transforms that into a 2-D coordinate that is then wirelessly communicated to that person's smartphone. Like SATURN, it uses RF backscatter to communicate the touch point, but it leverages the existing, ambient FM radio signal in our environment to provide an even more practical version of passive wireless communication. This enables paper-like surfaces to become active surfaces, such as the poster shown in Figure 1; a simple swiping gesture on the advertised event will cause that event to be saved on the individual's calendar. While the electronics for UbiquiTouch are simple, they are not currently manufactured in a way that is as thin and flexible as the touch surface.

SilverTape*

While inkjet printing of electronics has shown great promise over the last decade,[9] there are some limitations on the size of the printed circuit and the kinds of surfaces that serve as the substrate. SilverTape is a simple yet novel fabrication technique to transfer inkjet-printed circuit traces from paper onto versatile tape exchange substrates, without time- or space-consuming processes like screen printing and heat sintering.[10] These exchange substrates offer properties like flexibility, transparency, heat durability, and even water solubility. The technique leverages the commonly undesired low adhesion property of the inkjet printing films, and repurposes these films as temporary transfer media. The new tape substrates can be attached to a wider variety of (nonplanar) surfaces and can be chained together to create large printed electronics surface, opening up a variety of application opportunities.

*SilverTape was done in collaboration with colleagues at CMU.

NEED FOR COMPUTATIONAL MATERIALS

The history of interactive computing technology shows that what drives the adoption of new technologies are key applications that compel consumers to buy and companies to invest in necessary infrastructure.[11] So, what are the compelling applications of computational materials?

The paper-like multilayer material of SATURN detects mechanical vibrations, such as sound. We can envision a version of SATURN that would result in computational Post-It notes, flexible, paper-like notes that do everything a current Post-It note can do, but also can sense sound (or taps) and transmit that information elsewhere. It could record voice notes, or accept simple acknowledgment feedback. It might also be used to create an easily deployed wireless glass break detector, or serve as a monitor on heavy machinery to help determine when safe operational parameters are exceeded. In the shape of a protective face mask, it could sense and transmit coughs for remote analysis or act as a microphone to allow a quarantined individual to speak to someone else. It could be used as an active decorative element, as shown in Figure 1. For OptoSense manufactured using printed organic elements, we could create a version of an activity tracker that required no batteries, was waterproof, comfortable, and much less expensive than the $100 trackers people buy today. Office furniture could track usage patterns by recognizing movements of people (without identifying them) around tables, chairs, desks, and doorways. UbiquiTouch could evolve into a simple and cost-effective way to receive human feedback in any environment.

The list of ideas could go on for the other technologies described above, as well as the many other prototypes that are emerging. But are any of these compelling enough *by themselves* to warrant investment by the companies that would need to create them and build a market? Probably not. The big challenge for prototyping new and compelling user experiences is to demonstrate the value of a simplified large-scale distribution of solutions. The example of a road surface sensing capability at the beginning of this article points to a compelling opportunity, but only if we think very differently about how to scale up the manufacturing of this kind of computational solution. There is potential for an alternative computing industry that leverages the power/scale/form factor advantages of computational materials. One thing is certain, computational materials need to be put in the hands of creative designers who are better trained to explore the compelling use cases.

ADDITIONAL RESEARCH CHALLENGES

Beyond new user experiences that compel investment in and adoption of computational materials, there are a variety of other important research challenges.

Practical Power Provisioning

Two directions should be simultaneously pursued with respect to satisfying the power provisioning for computational materials: harvesting energy and direct wireless transmission of power. These are both maturing areas of research, but usually are not placed in tandem with the additional constraints of scale and form factor that we propose for computational materials. I address harvesting here.

A particularly promising direction for harvesting is to develop self-sustaining sensors, ones that harvest energy directly from the phenomenon being sensed, as demonstrated with triboelectric nanogenerators.[5,6,12] What other phenomena in the world (e.g., water, other chemicals) can spur our imagination?

An entire line of research could be dedicated simply to retrofitting existing spaces with computational capabilities, but a big concern is power availability and ease of the retrofit, that is, requiring no wires to an external power source. How do we explore environments where a computational need exists to determine how power can be harvested at that location? For example, we might be able to retrofit the exhaust pipe of an automobile with a thermoelectric harvester that powers a backup detection system, or use a miniature wind turbine to power a pedestrian-facing display to communicate driver intent at a crosswalk. Getting designers to think about retrofitting self-sustaining computational capabilities requires providing both a design process and appropriate tools to explore and build examples.

Production Practices

Somewhat hidden in the industry mantra of Moore's Law is the assumption that progress in computing manufacturing relies on increasingly sophisticated *integrated* manufacturing techniques. Integrated manufacturing techniques are not the only way to do mass manufacturing, as is evident in other noncomputing industries. Experts in the industry point to the fundamental and economic limitations of some of the critical techniques of integrated manufacturing, such as photolithography.[13] Over the past few years, my conversations with colleagues in materials science and chemical engineering have convinced me that computational materials for the IoM requires inclusion of a *bulk* manufacturing approach, as opposed to a completely integrated one. Chemicals are already produced at enormous throughputs, a capability enabled by two key processes: bottom-up synthesis; and separation. These processes occur in bulk (i.e., volumetrically) rather than on surfaces (i.e., areally) to enable favorable scale-up.

We should start thinking of computational materials as being produced from more basic "microchemicals," or nanoelectronic devices (e.g., transistors, diodes, etc.). While many micro/nanoscale objects have been bottom-up produced in recent years, achieving the level of structural complexity and/or hierarchy needed for nanoelectronic devices in a fully bottom-up fashion remains challenging. My colleagues at Georgia Tech have demonstrated bottom-up masking and etching steps that help to create devices, such as an npn-transistor, that can then be used in a "device ink" in the creation of circuits.[14,15] Newer additive manufacturing techniques, such as electrohydrodynamic (e-jet) printing promise fine control that can be exploited to connect these arbitrarily deposited microchemical on some surface.

Even before we can achieve high throughput, bottom-up bulk manufacturing of computational materials, we should democratize the creation of computational materials. In the same way that 3-D printers, laser cutters, and Arduino-based electronics have seeded the maker movement for Weiser's ubicomp, these new manufacturing techniques for computational materials should be simplified so as to support DIY for quick experimentation with the IoM. As I stressed earlier, developing compelling uses of computational materials relies on placing the power of computational materials in the hands of creative designers. Therefore, DIY computational materials should advance in lock-step with high throughput bulk manufacturing as a research priority.

Programmable Platforms

Computational materials will not be standalone solutions for any significant problems; they will exist as part of a larger system that involves traditional infrastructure. The overall system (or platform), therefore, will be partitioned into two parts. 1) The *computational material* that comprises an object that interacts directly with the physical world and humans and is energy-constrained, possibly mobile, and wireless; and 2) The *infrastructure* that is unconstrained in both energy and computational capability. How to design and program these hybrid computational platforms is a key challenge. Designing an overall system that optimizes over computational material and infrastructure will need programmatic support.

The earliest examples of computational materials are those that are wireless sensors. With mass deployment, this form of the IoM will result in much more sensed data that would feed into data analysis systems, but with data coming at unprecedented scale and spatial resolution. This will require programming capabilities to handle the decision points for when data is transmitted and stored in raw form and when it is synthesized into higher level information.

Some computational materials will be intentionally short-lived and disposable (e.g., a computational Post-It). Their functionality can afford to be static and very tailored to the purpose of the short-lived object. Long-lasting computational materials—embedded in/on materials like drywall, furniture, or roadways—will require a programmable architecture to be modified for different or improved functionality. The computational architecture embedded into longlived computational material must be reconfigurable over the life of the material.

Value-Sensitive Design Principles

Inventors of computational materials and the IoM can and must confront societal values as part of their research. Many of the bad (and good) uses of novel technologies come about through emergent properties of the invention, that is, they arise as use cases after a technology was developed and deployed. Privacy-by-design advocates, and in general proponents of value-driven design, recommend that technologists consider very seriously the potential repercussions of their work as it is being developed. While my aim is to inspire researchers to work in the area of computational materials, I cannot stress enough the importance of considering from the outset the implications of this new technology on our core societal values. In doing so, we can concretely influence the capabilities of computational materials and the IoM.

The example of SATURN as an inexpensive wireless microphone. Do we want to use this computational material to create wallpaper that can sense and transmit (and thus, record) all of the sounds in a given room? For some rooms, this might be a useful feature, but many would be uncomfortable with this, particularly if it is not clear that the recording was happening. How can you design a form of SATURN that has the audio recording capabilities, but also that respects the tenets of privacy-by-design? To do this methodically involves building an understanding of the threat models that exist with wireless audio recording and the issues of notice and consent that are required, both by legal standards and social norms. The technology itself has properties of locality, meaning it cannot record voice from a great distance away and it can only transmit audio a certain distance to certain infrastructure. Notice of recording can be built into the material in a self-sustaining way using electrochromic inks or other e-inks, providing the equivalent of a recording light. The functionality of the recording can also be designed such that a human has to do something extra to get recording to work, such as place a finger on the material to complete a circuit for transmission.

Thinking beyond privacy, we could also determine that such a computational material must be constructed from renewable sources or be biodegradable or nontoxic. With serious attention to values from the outset, and the control we can exert when we get down to the actual physical materials used in manufacturing, we can invent computational materials that do interesting things and preserve important values. Such unprecedented control compels us to exercise it in service of shared societal values.

THINKING DIFFERENTLY

Weiser inspired us by forcing us to think differently about the size and usage patterns of computers. This vision of computational materials is similarly motivated. Indeed, inspiration is critical at this time, because there are so many challenges to overcome and it will take a community to address them. Significant technical challenges and a desire to deliver meaningful value while guarding against violations of greater societal values can only happen if we are fueled by the passion of this vision.

We must force ourselves to begin thinking differently about computing. We can no longer rely on “Moore’s Law thinking” (everything will get smaller, cheaper, and more powerful over time); we should consider different forms of progress (more functional computational materials will get more self-sustainable, cheaper to produce at large scale and more similar to physical objects). One of the best ways to think differently is to seek influence from different fields, as I have done with my materials science, chemical engineering, and design colleagues at Georgia Tech. In the case of computational materials, significant dialogue between materials science, chemical engineering, electrical and computer engineering, computer science, and design is needed. Weiser’s vision united the last four disciplines. Computational materials and the IoM must engage the first two disciplines more seriously.

A future issue of *IEEE Pervasive Computing* will be dedicated to this topic of computational materials and the IoM. We look forward to seeing the work being done in our community (and others) that reflects this vision, and likely improves upon it.

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