The Next Revolution in Materials

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Teleprompter script

“Good morning. My name is Mitch Zakin, and I am a chemist and inventor. I joined DARPA because it is unfettered by conventional wisdom—a place where one can both envision and create the future.

My vision for that future involves a concept so simple, yet so revolutionary that it pushes even the DARPA envelope. A vision that has profound implications for how we think about chemistry and materials. A vision that could provide our warfighters with meaningful technological surprise in the form of better tools at lower cost, and better logistics and supply trails that are simpler and easier to manage. My vision lies in the concept of Programmable Matter—the next revolution in materials.

What is Programmable Matter? Programmable Matter is a user-programmed smart material that adapts to changing conditions, in order to maintain, optimize, or even create a whole new functionality, using means that are intrinsic to the material itself. From a military perspective, Programmable Matter is the ultimate way to prevent technological surprise—by having materials, such as polymers, metals, or composites, adapt to future operational environments. As Dr. Tether said, the future is uncertain, but we can help the warfighter be ready by shaping the future with opportunities. Programmable Matter is just such an opportunity.

I find my inspiration for Programmable Matter in a concept I like to call “RetroScience,” reaching “Back to the Future” to create new capabilities. Consider these recent, but vintage, insights.

Information carrying materials were demonstrated in the 1980s.

Electrets, the technology behind the Xerox copying process, have potential as building blocks for reconfigurable and addressable materials.

Tribocharging, the phenomenon behind static electricity, has been harnessed to reversibly assemble complex structures.

And finally, **Jamming Phenomena**, the means by which meso-scale objects, such as peanuts and sand, “lock” together, can create matter with astounding reversible changes in mechanical properties. Sand and water become as strong as stainless steel!

So I ask myself the question, **“***Why can’t synthetic materials be programmed to adapt to the* *environment through smart processes?"*

Let's first look at some futuristic examples that illustrate the power of Programmable Matter: Imagine an amorphous material that can be programmed to instantly become a hammer, a wrench, or a screwdriver on demand. And then return to its initial form—so it can be reused. This would be an "Instant Toolkit," and the impact on logistics would be phenomenal.

It gets even better. From Programmable Matter we could build materials and even smart machines that adapt to their surroundings, such as an airplane wing that adjusts its surface properties in reaction to environmental variables. We would no longer be constrained by the installed version of a system—constant feedback from the operational environment would ensure that we always have the latest capabilities. We could make a wrench that conforms automatically to any size bolt. Or a universal spare part that assumes the right size, shape, compliance—and function—to repair anything. One size DOES fit all. Imagine clothing that maintained normal body temperature in both the arctic and the desert. The possibilities are endless… Achieving such functionality forces us to think about chemistry in a fundamentally different way—even to redefine what we mean by the term "material."

The key to realizing Programmable Matter resides in two radical, but complementary, ideas: The first is **The Convergence of Chemistry, Information Theory, and Control,** a concept I call "InfoChemistry"—building information into materials. The second is a new functional form of matter based on Meso-scale building blocks, a concept I call **MesoMatter**. Taken together, these two ideas provide a powerful foundation for Programmable Matter.

First and foremost, Programmable Matter must encode information, intrinsically sense the environment, process data inputs, and efficiently flow this information to all parts of its structure. **Information Flow is the basic engine of Programmable Matter.**

A rigorous mathematical framework for Information Flow—the encoding, transmission, and selection of messages—in the presence of noise—was formulated in the groundbreaking work of Shannon in the 1940's. Shannon described Information Flow in terms of entropy, a basic chemical property that is central to Energy and Mass Flow in materials. This fundamental connection between chemistry and information—InfoChemistry—has important consequences—specifically, the creation of new phases of matter—and new phase transitions—that are hybrids of both material and information state.

We're all familiar with chemical phase transitions such as freezing (liquid-to-solid) and its inverse, melting (solid-to-liquid). With InfoChemistry, there is a richer palette of accessible states. We can have a transition from an *Info-liquid*, where both matter and information are fluid, to an *Info-solid*, where matter and information are more localized. Or to a state where information is fluid but matter is localized. **This is the new thermodynamics of Programmable Matter.**

So the basic question is: how do we construct synthetic materials that follow the logic structure of Information Theory?

A possible answer to this question lies in a powerful yet simple mathematical construct known as a Cellular Automaton. This mathematical entity consists of a grid of “cells”—in 3 dimensions each cell is conceptually a geometric solid—that interact according to a set of rules. A new generation is created each time the programmed rules are applied to the entire grid. Even with simple rules, Cellular Automata adapt to changing environments**.** There are even versions which are equivalent to a Universal Turing Machine, which means they can compute anything that is expressible in algorithmic form. Cellular Automata are their own information processing system!

What we need is a chemical analogue – so let me introduce you to MesoMatter. MesoMatter is a new functional form of matter constructed from building blocks ranging in size from 1 micrometer to 1 centimeter. These building blocks, denoted “MesoParticles,” can have a variety of sizes, shapes, composition, and functions, which when combined, form a dynamic material.

MesoMatter has several critical features. First, building blocks at the MesoScale are big enough so that intricate structures with real functionality, such as plumbing and ratchets, can be constructed. Plumbing could be gears, fluidics, machines, or even computers. Furthermore, with MesoParticles we can build macroscopic objects. Try doing that with nanoparticles!

Second, MesoMatter adapts to external stress by either changing individual MesoParticles, or by arranging fixed particles into new configurations. MesoParticles communicate and interlock with their neighbors to create dynamic bulk structures with mechanical integrity.

Third, the structure and function of individual MesoParticles are completely separable. The external geometry determines packing, assembly, and bulk structure. The interior has the machinery to process information, generate action, etc. This simple notion yields complete control over information flow and mechanical properties, both locally and globally. Combined with methods for reconfigurable assembly, separability can be exploited to create materials of unprecedented complexity and capability. Each building block in MesoMatter can be considered a specialized machine, with specialized functions, such as encoding, processing, or transmitting information.In fact, individual MesoParticles may be computers, wireless transmitters, or even combinations of these with materials. By doing this, **MesoMatter achieves materials with extreme functional plasticity.**

Now that we have a conceptual framework for Programmable Matter, what new scientific and technological breakthroughs are needed? We need *your* ideas for designing materials that optimize Information Flow—and for mathematical models and design rules that make this a tractable problem for real-world applications.

We need *your* ideas for fabricating, transporting, and assembling MesoParticles with the right stuff—and for ways to lock them together

We need *your* ideas for building information directly into chemistry—and for seamlessly fusing materials and machines.

Most of all, we need *your imagination and creativity* to make Programmable Matter a reality.

Let's now return to the practical implications of Programmable Matter. If we could really do this, Programmable Matter would fundamentally change "everything." Product development would be streamlined to sets of "universal designs," and manufacturing would be reduced to making programmable components and simply mixing them together.

What does this mean for the warfighter? Better tools, at lower cost, that last longer and operate under all conditions. Logistics and supply trails that are simpler and easier to manage. And perhaps most important, <u>control</u> of surprise on the battlefield.

Programmable Matter is the ultimate interdisciplinary endeavor... It will take the combined efforts of chemists and material scientists, physicists and biologists, cognitive scientists and mathematicians—and information theorists—to pull it off. Do you have the inspiration, the desire, the funding to pursue this vision? We can't help you with the first two, but…

If you have ideas for realizing Programmable Matter, come see me at the DSO booth and we'll talk. I look forward to seeing you <u>beyond</u> the "Far Side of the Far Side." Thank you.

Next is Ben Mann—a program manager who is passionate about mathematics.