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Make Your Own World With Programmable Matter

People will conjure objects as easily as we now play music or movies

By **Philip Ball**

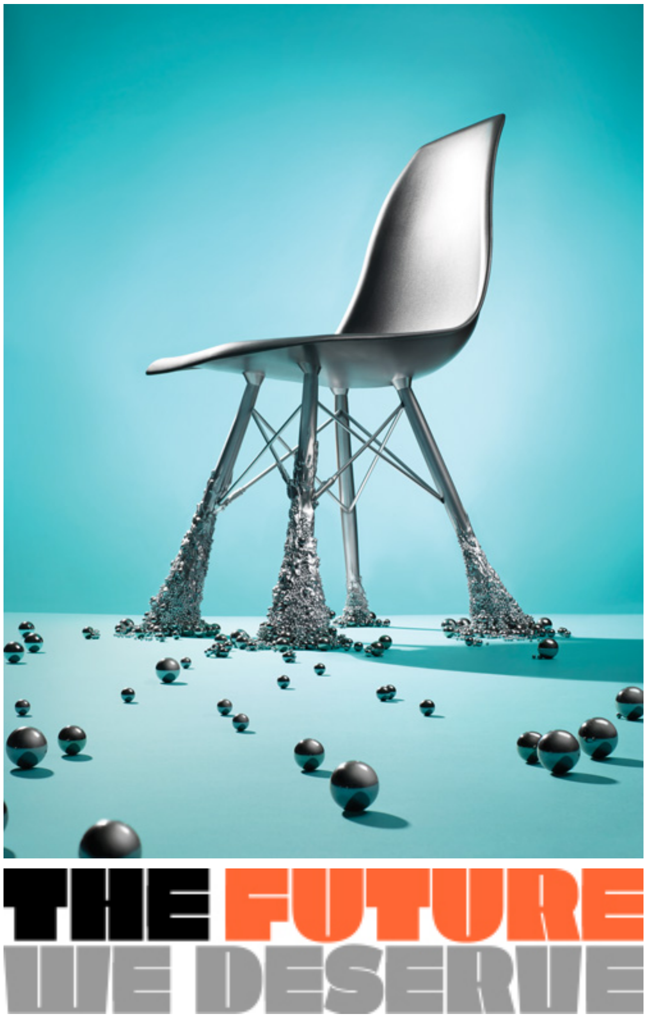

Photo: Adam Voorhes; Prop Stylist: Robin Finlay

Several executives listen attentively to a sharp-suited sales rep making his pitch. Suddenly, a miniature car emerges from a vat of gray goop in the center of the conference table. The salesman proceeds to reshape this model using nothing more than his hands, flattening the car's roofline and adjusting the geometry of its headlamps. Finally, he transforms the car from its initial haze gray to fire-engine red, its "atoms" twinkling in close-up with Disney-movie magic as their color changes.

Yes, it's just a video done with special effects. But it comes from researchers at Carnegie Mellon University, in Pittsburgh, who are developing technology intended to enable not just the instant creation of complex objects—far beyond what today's 3-D printing can achieve—but also their transfiguration on command.

Such a capability could change society even more profoundly than the Internet has. If this magical morphable matter were cheap and effective, it would allow us to send and download copies of objects as easily as we do digital documents. We could duplicate an object and then reshape it to our whims. Even if the technology turns out to be too expensive or the objects too fragile to replace conventionally manufactured goods, it might still allow people to summon up a facsimile of the thing they desire long enough to test it out, try it on, redesign it, or be entertained by it—with no more effort than it now takes to view a digital movie or play an MP3 file.

But do such wild notions bear any relation to what might actually be possible over, say, the next 50 years? To get a sense of the answer, it's helpful first to look back a quarter century or so to the roots of this audacious concept.

WHAT COULD POSSIBLY GO WRONG?
[sidebar]

In 1991, MIT computer scientists Tommaso Toffoli and Norman Margolus speculated in print about a collection of small computers arranged so that they could communicate with their immediate neighbors while carrying out computations in parallel. A large number of such computing nodes would together constitute "programmable matter," according to Toffoli and Margolus. They were talking only about a highly parallel modular computer, one that might simulate the physics of real matter. But soon others applied this same term to a far more ambitious idea: an assembly of tiny robotic computers that could rearrange themselves to take on varying forms.

The chemistry Nobel laureate Jean-Marie Lehn independently developed related ideas even earlier, but coming from a different direction. He and others argued that chemists would use the principles of self-organization to design molecules imbued with the information they needed to spontaneously assemble themselves into complex structures. In the 1980s, Lehn began calling this "informed matter," which would be a kind of programmable matter constructed at the atomic and molecular scale.

Programming Matter From the Bottom Up

Chemists, too, hope to fashion programmable forms of matter

Engineers' top-down approaches to programmable matter will build on existing developments in robotic technology. But there are also bottom-up strategies, using nanoscale particles or even molecules. For example, there is intense research being done on self-propelled or "living" colloids: particles perhaps a hundred or so nanometers across that have their own means of propulsion, such as chemical reactions that release gas.

The last decade or so of research in nanotechnology—with its interest in "bottom-up" self-organizing systems—has lent increasing support to Lehn's ideas. But creating molecules that can assemble into complex and even responsive forms is one thing; designing systems made from tiny computers that will reconfigure themselves into whatever you want at the push of a button is a whole other kind of challenge. For that, it's the engineers who are now taking the lead.

The shrinking of power sources and circuitry for wireless communications now allows robots, even centimeter-size ones, to talk to one another easily. And making miniature machines that can change shape or orientation without requiring delicate moving parts is increasingly practical, thanks to the development of smart materials that respond to external stimuli by bending or expanding, for example.

In short, in the three decades since the basic ideas of programmable matter were first formulated, the technologies needed to create concrete examples have arrived and are actively being tinkered with.

These particles, made from materials like magnetic crystals encapsulated in polymer spheres, can exhibit complex, self-organized behavior. They can, for instance, form crystalline patterns that break or even explode and then re-form. Choreographing these changes is impossible at the moment, but researchers have shown they can move and control individual nanoparticles using radio waves and magnetic fields. These same techniques have also permitted wireless remote control of certain processes in living organisms, such as the triggering of nerve signals and the release of insulin. So it's not too huge a leap to envision their use in some future form of configurable matter that might be used to modify, heal, or control living things.

Researchers have also been studying ways to turn DNA itself into a kind of programmable material that could be made to assemble into specific configurations using the same chemical principles that bind the double helix of the genome. In this way, scientists have woven strands of DNA into complex nanoscale shapes: boxes with switchable lids, letters of the alphabet, even tiny world maps. By supplying and removing "fuel strands," which can temporarily stick to and change the shape of other strands, it's even possible to make molecular-scale machines that move.

Eventually, such DNA bots might be given the ability to replicate and evolve, at which point this variety of programmable matter could become increasingly complex and capable on its own.

—P.B.

Seth Goldstein and his team at Carnegie Mellon, in collaboration with others at Intel Research Pittsburgh, were among the first to put together prototypes and explore possible applications.

Goldstein and his colleagues envision millions of cooperating robot modules, each perhaps no bigger than a dust grain, together mimicking the look and feel of just about anything. They hope that one day these smart particles—dubbed claytronics—will be able to produce a synthetic reality that you'll be able to touch and experience without donning fancy goggles or gloves. From a lump of claytronic goop, you'll be able to summon any prop you want: a coffee cup, a scalpel, or (as their promotional video illustrates) a model automobile to use in a sales presentation.

"Any form of programmable matter that can pass the Turing test for appearance [looking indistinguishable from the real thing] will enable an entire new way of thinking about the world," says Goldstein. He also entertains the notion that objects built from programmable matter could be fully functional, in which case the possibilities for this technology become so limitless as to boggle the mind. "Applications like injectable surgical instruments, morphable cellphones, and 3-D interactive life-size TV are just the tip of the iceberg," says Goldstein.

The Carnegie Mellon team calls the components of this stuff "catoms," short for claytronic atoms, tiny spherical robots that are able to move, stick together, communicate, and compute their location in relation to others. Making them is a tall order, especially if you need millions. But Goldstein thinks it's achievable.

Since the early 2000s, he and his fellow Pittsburgh researchers have been building modest approximations of their ultimate goal. The first prototypes were squat cylinders, each a little bigger than a D-cell battery, their edges lined with rows of electromagnets, which allowed them to stick to one another and form two-dimensional patterns. By turning various magnets on and off in sequence, the researchers could make one catom crawl around another. More recently, the team used photolithography to build cylindrical catoms about a millimeter in diameter, which can receive power, communicate, and adhere. These tiny catoms can't yet move, but they will soon, Goldstein promises.

The key challenge is not in manufacturing the circuits but in programming the massively distributed system that will result from putting all the units together, says Goldstein. Rather than drawing up a global blueprint, the researchers hope to use a set of local rules, whereby each catom needs to know only the positions of its immediate neighbors. Properly programmed, the ensemble will then find the right configuration through an emergent process.

Some living organisms seem to work this way. The single-celled slime mold *Dictyostelium discoideum*, for example, aggregates into a multicellular body when under duress, without any central brain to plan its dramatic transformation or subsequent coordinated movements.

For catoms to do that, they must first be able to communicate with one another, if not also with a distant controller. The Carnegie Mellon researchers are now exploring electrostatic nearest-neighbor sensing and radio technologies for remote control.

Of course, to be practical, the repositioning of catoms needs to happen fast. Goldstein and his colleagues think that an efficient way to produce shape changes might be to fill the initial blob of catoms with lots of little voids and then shift *them* around to achieve the right contours. Small local movements of adjacent catoms would be sufficient to shift the cavities, and if they are allowed to bubble to the surface, the overall volume would shrink. Conversely, the material could expand by opening up pockets at the surface and engulfing them.

At MIT, the computer scientist Daniela Rus and her collaborators have a different view of how smart, sticky grains could reproduce an object. Their "smart sand" would be a heap of such grains that stick together selectively to form the target object. The unused grains would just fall away.

Like Goldstein, Rus and her colleagues have so far built only rather large prototypes—"smart pebbles"—that work in two dimensions, not three. These units are the size of sugar cubes, with built-in microprocessors and electromagnets on four faces. A set of cubes can duplicate a shape inserted into the midst of a group of them. The ones that border the target object recognize that they are next to it and send signals to a collection of other cubes elsewhere to replicate its shape.

Rus's team hit on an ingenious way to make smart grains move, demonstrating the strategy using larger cubes they call M-blocks, which are 5 centimeters on a side. Each uses the momentum of flywheels spinning at up to 20 000 rotations per minute to roll over, climb on top of one another, and even leap through the air. When they come into contact, the blocks can be magnetically attached to form the desired configuration. At the moment, the experimenters must provide the instructions for sticking together. Their plan, though, is to develop algorithms that allow the cubes themselves to decide when they need to hook up.

Video: MIT Distributed Robotics Lab

The researchers' ultimate aim is to create a system of modules the size of sand grains that can form arbitrary structures with a variety of material properties, all on demand. Shrinking today's robotic pebbles and blocks to the submillimeter scale presents an enormous technical challenge, but it's not unreasonable to imagine that advances in microelectromechanical systems might allow for such miniaturization a few decades from now. That would then allow someone to instantly reproduce a facsimile of just about any object—depending on what it is, maybe even one that functions as well as the original.

While the holy grail is a sea of tiny machines working together to perform such magic, Goldstein sees the basic ideas of programmable matter being applied to objects at all scales, from atoms to house bricks, or perhaps even larger. It's almost a philosophy: a determination among today's researchers to make their creations more intelligent, more obedient, and more sensitive, imbuing them with qualities that will eventually make them act almost like living things—like matter with a mind of its own.

WHAT COULD POSSIBLY GO WRONG?

Help, My Chair Has a Virus!

Hackers could turn your programmable matter against you

Illustration: MCKIBILLO

There is something a little sinister in this idea of matter that morphs and even mutates. Can we be sure we can control this stuff? Here our fears are surely shaped by old myths like the golem of Jewish folklore, a being fashioned from clay that threatened to overwhelm its creator.

The malevolence of matter that is infinitely protean is also evident in popular culture, for example the "liquid robot" T-1000 of *Terminator 2: Judgment Day* (1991). The prospect of creating programmable matter this sophisticated remains so remote, though, that such dangers can't be meaningfully assessed. But in any event, Seth Goldstein of Carnegie Mellon insists that "there's no gray-goo scenario here," referring to a term that nanotechnology visionary K. Eric Drexler coined in his 1986 book *Engines of Creation*.

Drexler speculated about the possibility of nanobots that could self-replicate exponentially as they consumed the raw materials around them. This sparked some early fears that out-of-control nanotechnology could turn the world into a giant mass of gray sludge— a theme that appeared repeatedly in later works of science fiction, including Wil McCarthy's 1998 novel *Bloom*, the late Michael Crichton's 2002 thriller *Prey,* and even in tongue-in-cheek fashion in a 2011 episode of the animated TV sitcom "Futurama."

The real threats may be ones associated more generically with pervasive computing, especially when it works by means of Wi-Fi. What if such a system were hacked? It's one thing to have data manipulated online this way, but when the computing substrate is tangible stuff that reconfigures itself, hackers will gain enormous leverage for creating havoc.

But Goldstein thinks that the actual dangers are more of a sociological nature. Programmable matter is sure to be rather expensive, at least initially, and so the capabilities it offers might only widen the gap between those with access to new technology and those without. Want to relax on your home holodeck? Enjoy it if you can afford one. If not, you'll have to content yourself with playing *Grand Theft Auto XXXVII*.

And if programmable matter becomes capable of producing fully functional objects, that development, much like today's pervasive automation, will threaten to render jobs in traditional manufacturing obsolete. So serious advances in programmable matter will probably make more people unemployable, not because they lack useful skills but because there will be nothing for them to do.

Of course, powerful new capabilities always carry the potential for abuse. You can see hints of that already in, say, plans to use swarm robotics for surveillance or in the reconfigurable robots that are being designed for warfare. Expect the dangers of programmable matter to be much like those of the Internet: When just about everything is possible, not all of what goes on will be good. *—P.B.*

This article originally appeared in print as "Infinitely Malleable Materials."

About the Author

Philip Ball holds degrees in chemistry and physics and was a physical sciences editor at the journal *Nature* for many years. He first began covering the topic of programmable matter a decade ago while working on a radio program for the BBC. “In the information age, it seems inevitable that we’re eventually going to start building information, and computation, into the building blocks of matter itself,” says Ball.

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