toxicity as part of the product development process. Even the largely unregulated cosmetics industry funds independent studies and adheres to the FDA's stringent voluntary guidelines.

Nanotechnology also engenders concerns about the environment. Even if nanoparticle safety guidelines for particular applications are established, what if the particles are taken out of the realm of their intended use? For example, if nanoparticles are deployed in electronics and deemed safe because they are closely bound within the matrix of a circuit board, what happens if they are released into the environment when the circuit board is destroyed or disposed of? What if it catches fire? And what about waste disposal and nanotech-enabled manufacturing plants?

Again, all of these questions are predicated on the unfounded idea that nanoparticles are fundamentally more dangerous than other materials. As with any set of chemicals used in manufacturing at any scale, there should be standards about how various types of nanoparticles are handled. The National Institute for Occupational Safety and Health recently issued an initial set of best practices and safety guidelines. This is an important first step, but neither the Occupational Safety and Health Administration nor the EPA has regulations for the handling of nanoparticles (though both groups are discussing them).

Thus far, a combination of public attention and industry self-regulation has kept the nascent field safe. Nanophase, one of the few companies that makes nanoparticles in industrial quantities, sets a high standard for safety practices, operating a closely controlled and environmentally sensitive production line. Because of the precision of its production process, Nanofilm, another industrial-scale producer of nanotechnology, is able to carefully capture its waste. The waste stream is also considerably smaller than that resulting from other chemical process—in the case of Nanofilm, its annual waste stream fits into one 55-gallon drum.

This oversight and discussion is good, so long as it continues on track, or as closely as possible, with the pace of research. Halting development because of unfounded concerns would have only a profoundly negative impact for a world facing environmental hazards, disease, and other challenges that nanotechnology could lessen or resolve. Nanotechnology is in its gangly adolescence and needs time and space to grow. In the parlance of the *Bulletin*, it is not minutes from midnight, but rather minutes from dawn. ⚛

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# The stealth threat

## AN INTERVIEW WITH K. ERIC DREXLER

Technological innovations might help fight terrorism and prevent wars, but some may become the tiny engines that rule our lives.

SCIENTIST AND AUTHOR K. ERIC DREXLER is an expert on the benefits and dangers of technological innovation. His groundbreaking books on molecular manufacturing *Engines of Creation* (1986) and *Nanosystems: Molecular Machinery, Manufacturing, and Computation* (1992) have defined the fledgling field of nanotechnology. As the cofounder of the Foresight Nanotechnology Institute and currently the chief technical adviser to the software company Nanorex, Drexler's many concerns include the possibility of a miniaturized arms race and the spread of mass infotainment. Senior Editor Jonas Siegel asked Drexler to assess nanotechnology's likely impact on the future.

**BAS:** *How do you see nanotechnology, specifically molecular manufacturing, affecting the development of new types of weapons?*

**DREXLER:** To identify molecular manufacturing's capabilities, it helps to understand its physical principles. For example, scaling down simple machine components, like shafts, gears, and bearings, from centimeters to nanometers (and systems from tens of meters to microns) increases components' motion frequencies by a factor of about 10 million. For a machine assembling things, manufacturing throughput will increase by the same factor. Richard Feynman discussed this principle when he introduced the ideas behind molecular manufacturing in 1959. High throughput helps make the products inexpensive.

Of course, literally scaling down an ordinary manufacturing system would make no sense because parts behave differently at the molecular level. Assembly operations couldn't use tiny hands; they'll use molecular tools that transfer molecular fragments by shifting bonds. I'd call this a chemical process, but that would suggest random thermal motion. Molecular manufacturing systems will instead mechanically guide each molecular fragment to a specific reactive site on a component under construction, and nowhere else. For this to be reliable, the structures must be rigid enough to limit thermal motion, and the transfer step must use up a substantial amount of free

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energy. Scientists have identified many other constraints, but design and modeling work shows that these constraints can be met, allowing nanoscale manufacturing systems to build structures with atomistic precision.

The manufacturing processes become more conventional at larger sizes. The smallest components can be passed to an array of larger machines to assemble them into larger components, and so on up to the macroscopic scale. This process can make human-scale products that contain computing devices near the physical limits of miniaturization, materials near the physical limits of strength, and so on. An advance this fundamental will affect technologies across the board, including weapons.

**BAS:** *How will systems like these be developed, and when?*
**DREXLER:** I've studied what physics tells us that technologies can do, but method can't calculate a date on a calendar. However, a basic step in development is to understand where it can go. Physical systems of the sort needed for advanced molecular manufacturing can be *modeled* today, but can't be *made* today. This should be no great surprise—there are many examples of things that can be modeled but not made, or made but not modeled.

## EXPERT TESTIMONY

### Do-it-yourself biotechnology

**DREW ENDY:** Assistant professor at the Biological Engineering Division at MIT.

Prior to DNA sequencing and synthesis, genetic material and biological information existed as physical stuff and propagated through time from one generation to the next. Sequencing lets us create a new layer, an information layer. Genetic information can propagate on computer databases, independent of physical reproductions. Synthesis lets us recompile the physical stuff from the information, making genetic material and genetic information interconvertible.

I imagine a future where individuals working on computers are the biological engineers. They ship their sequence information via the wireless internet to a foundry somewhere, which then drop ships the corresponding genetic material by overnight delivery somewhere else. That is why I am skeptical when people talk about control mechanisms such as licensing everybody who is doing biological engineering or biotechnology research, or making them take a course. You're really going to be talking about everybody with access to a laptop.

Physical models are good enough to answer the general questions about molecular manufacturing regarding scale, speed, energy requirements, heat and mass transfer, and so forth. To make this work, though, it's important to choose designs that use only well-understood materials and phenomena, and not to push too close to any physical limits. What people eventually build will of course be cleverer than this.

Computational modeling provides a kind of low-resolution imagery of potential destinations for technology, much as telescopes have provided low-resolution imagery of potential destinations for spacecraft. The visible promise of advanced capabilities in molecular manufacturing, however, has sometimes distracted attention from intermediate objectives and ongoing lab work.

**BAS:** *What types of weapon systems do you think could be made using molecular manufacturing?*
**DREXLER:** A conventional manufacturing process can make systems if it can make their components, and this depends on materials, precision of fabrication, and so forth. With bottom-up manufacturing, though, the smallest components are atoms, not pieces of material. Putting them together according to design makes things with the greatest precision possible and the finest details. At this level, what we think of as "materials" look like assemblies of parts—perfect parts—and they're prefabricated by nature. This type of process could lead to a range of products, including military systems.

Here's a sketch of one possible system. A cruise missile today carries about a half ton of explosives to a target and costs about $1 million. With high-throughput, bottom-up manufacturing, $1 million could pay for missiles that deliver hundreds of tons, and not merely of explosives, but of submunitions and sub-submunitions that can disperse across a 100-kilometer radius. These could deliver, for example, 10,000 devices each weighing 1 kilogram, 100,000 weighing 100 grams, and 1,000,000 weighing 10 grams, with enough mass left over for 100 million or more in the 1-gram range. Even the smallest submunitions, about the size of a wasp, could have wings, a sophisticated guidance system, and the ability to kill or incapacitate people and many kinds of hardware. They might be programmed to act immediately, but a more interesting possibility is that they land, deploy solar cells, link to form a communications network, and watch. This suggests how easy it would be to deploy a fine-grained surveillance system with local force to back it up.

**BAS:** *How could this different manufacturing capacity affect the availability of these weapons?*
**DREXLER:** It depends on who has access to a sufficiently general-purpose manufacturing system. I think that there would be a very strong interest on the behalf of the presumably relatively large institutions that spearhead development to make sure that that kind of general capability

doesn't diffuse widely. Would it be something that a small group or individuals would have in hand? They could, in principle, but in practice, I don't think they would be able to get their hands on anything but systems with specialized capabilities.

**BAS:** *What type of skills would be needed to smoothly operate this capacity?*
**DREXLER:** Producing manufacturing systems will require skill for design, testing, and redesign. After that, the process will be fully automated, give or take some snap-together-style final assembly. There's no room for hands in machines that assemble nanoscale parts. If military systems include fine-grained surveillance, as I'd expect, then they would need a lot of pattern-recognition and decision-making capacity. With anything like today's software, only a limited part of that capacity could be automated. Above that level, there would be a need for many trained eyes.

**It's often said that we face an unending struggle against terrorism. This is nonsense. Advancing technologies will eventually make it easy to suppress terrorism. The great struggle will be to keep this power from supressing too much more.**

**BAS:** *Why is this possibility so dangerous?*
**DREXLER:** The most obvious concern is the destructive potential of cheap, abundant, deadly weapons. What I fear more, though, is the coercive potential of cheap, abundant, nonlethal weapons, some similar to types in use today, combined with ubiquitous surveillance. Killing and destroying are inexpensive ways to intimidate and incapacitate, but when the cost of surveillance and nonlethal weapons drops far enough, they will offer a practical and far more acceptable alternative to killing. You won't see wars, merely enforced disarmament and suppression of terrorism, and then perhaps suppression of assault, suppression of theft, suppression of spitting on sidewalks, and then perhaps suppression of dissent, offensive music, and so on.

We should be thinking about what this means for governance. It's often said that we face an unending struggle against terrorism. This is nonsense. Advancing technologies will eventually make it easy to suppress terrorism. The great struggle will be to keep this power from suppressing too much more.

**BAS:** *How would molecularly manufactured agents differ from agents manufactured today?*
**DREXLER:** "Better control" is a theme that runs through both the manufacturing processes and the products. Control of motion and behavior, though, has a price in size and complexity. I don't expect agents in the molecular to bacterial size range to be of great importance, because there are such great advantages to things that are much larger, yet still very small on a human scale. The smallest flying insects are a fraction of a millimeter long—about 1 million times the mass of a bacterium but one-millionth the mass of a honeybee. That's large enough to carry a gigahertz CPU and run it for hours before recharging. Numbers like these still surprise me.

**BAS:** *How should scientists and industry work to avoid a manufacturing process being exploited for harmful purposes?*
**DREXLER:** A general-purpose manufacturing technology is like a computer, and the maker of a general-purpose computer has no control over the kind of software that it will run. To take the analogy further, though, not every computing device is general purpose, and devices can be built with restrictions such as so-called digital rights management systems. Analogous restrictions would work better for manufacturing systems than they do for computers.

I expect the core technologies to be very general, in part because it will require very general capabilities to make the restricted systems. But perhaps that general capability can be kept under the control of a system of governance that enables wide access only to systems that make non-weapon products.

**BAS:** *What role should scientists play in this process?*
**DREXLER:** Most fundamentally, scientists should ensure that there is a widespread, basic comprehension of these technologies. For example, on the development side, it's important to recognize that the big danger isn't an accidental disaster, but deliberate abuse. Huge amounts of attention have been directed to theoretical scenarios in which tiny machines make more like themselves, and somehow do this without help, and accidentally become runaway replicators. As I've pointed out elsewhere, there's no known practical reason to make systems even remotely similar to these. If someone does find a reason to move in that direction, development would be difficult, and scientists should of course oppose it.

More generally, people need to understand the real opportunities. If you play out the implications of these technologies for raising standards of living, reducing environmental impact, and shifting to sustainable energy sources, the framework for policy decisions looks very different, and in some ways much more attractive. A better understanding of the basic technologies and potential positive outcomes could help prevent a rush toward a destabilizing arms race.

**BAS:** *Which technological achievement from the past 100 years threatens humanity the most?*
**DREXLER:** One could argue the greatest threat is one that works indirectly: the growth of mass infotainment, enabled by electronic media. It has evolved under a kind of natural selection that favors whatever holds people's attention, which has at best a loose connection with the truth. Disagreements about facts are twisted into conflicts between people; complex topics are simplified, mystified, or ignored; and any serious topic that bobs to the surface is washed away in a sea of sound bites, flashing images, and what passes for news. Because this overlays and crowds out other communications, it compounds every problem that could be lessened by a better-informed public.

**BAS:** *What threats should the public be focusing on?*
**DREXLER:** There are many that deserve attention, but climate change in particular needs public mobilization. Regarding molecular manufacturing, the first focus should be on how to use these technologies well, for example, by producing inexpensive solar arrays to power the removal and sequestration of carbon from the atmosphere, effectively putting global warming in reverse. This would require terawatts of electricity. The second focus, which can only be understood in the context of the first, should be on preventing these technologies from being used as instruments of illegitimate power.

At a social and political level, we need a workable concept of how safety and freedom can coexist with surveillance technologies. I expect that this will require a new framework of law regarding how surveillance information is stored, accessed, and used, and I expect that much of this law will be implemented at the hardware and software level. However, thinking about information technologies that follow laws is difficult today, because few people realize that the gross insecurity of modern computer systems has nothing to do with the basic nature of computation and everything to do with some bad choices made several decades ago. This can be fixed, and doing so should be a high priority.

**One could argue that the greatest threat is one that works indirectly: the growth of mass infotainment. It has evolved under a kind of natural selection that favors whatever holds people's attention, which has at best a loose connection with truth.**

**BAS:** *How would you explain to elementary school students the potential of molecular manufacturing to impact humanity?*
**DREXLER:** I'd say: Everything around us is made of atoms and molecules. In living cells, there are tiny machines that put molecules together to make things like potatoes and trees. People are learning to do this, and when we get good at it, we'll have machines that can make things like solar cells, computers, and spaceships. Like the machines that make the wood in trees, these machines will be able to make things with low cost and almost no pollution.

This technology could let everyone in the world have better things than the richest people can afford today, and at the same time start to undo damage to the environment. But like every powerful technology, starting with axes and fire, this one could be used to harm people and harm nature. As you grow up, I hope that you'll learn more about this technology and help to make sure that it is used well. Human beings can accomplish more than what your parents grew up believing.