Teeny Tiny Wireless

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Nanotechnology is the science of the future: it holds the promise of unimaginable technological advances—and unimaginable destruction.

"The bits were in motion. Microscopic machinery, smaller than ants, smaller than pins, working energetically, purposefully—constructing something that looked like a tiny rectangle of steel.

'They're building,' O'Neill said, awed."

In his short story *Autofac*, written almost fifty years ago, science fiction writer Philip K. Dick envisioned a world dominated by automatic factories producing miniscule self-replicating robots. While the world of *Autofac* was firmly entrenched in science fiction, the dangers and the possibilities he envisioned are fast becoming reality.

Nanotechnology is the science of manipulating structures on an atom by atom basis. It gets its name from the nanometer, a measurement equivalent to one billionth of a meter—about three or four atoms in width. Since Moore's Law predicts that the number of transistors on a chip will double every 18-24 months, it stands to reason that the 21^{st} century will see computers get much, *much* smaller.

The concept of building devices on a nanometric scale first moved beyond the realm of science fiction in a 1959 lecture by physicist Richard Feynman. "There is a device on the market, they tell me, by which you can write the Lord's Prayer on the head of a pin," he said. "But that's nothing; that's the most primitive, halting step in the direction I intend to discuss. It is a staggeringly small world that is below."

And just last April, scientists at IBM Research in Zurich and at the University of Basel built nanoscale biochemical "machines," arrays of silicon cantilevers which were made to bend in response to the presence of individual strands of DNA. Such machines could be used to detect defects in DNA, rapidly diagnose medical conditions, and even serve as a building block for micro- and nano-machinery.

Jim Gimzewski of IBM Research was struck by the enormous possibilities presented by the experiment. "We have found a way to get DNA to do the work for us, so we don't need batteries, motors or the like to operate tiny machines," he said. The robots of *Autofac* may not be that far off after all.

Man, Meet Machine

In 1986, K. Eric Drexler's book *Engines of Creation* suggested that the ability to manipulate atoms individually would precipitate a wide range of technological advances, including optimized computing, efficient space travel, and cell repair molecules that could clean the environment, fight cancer, and stop the aging process. Just about anything would become possible—even transforming coal to diamonds.

"Coal and diamonds, sand and computer chips, cancer and healthy tissue: throughout history, variations in the arrangement of atoms have distinguished the cheap from the cherished, the diseased from the healthy," he wrote. "Arranged one way, atoms make up soil, air, and water; arranged another, they make up ripe strawberries."

And in his 1999 book *The Age of Spiritual Machines*, Raymond Kurzweil took nanotechnology to the next level, envisioning the ultimate merging of man and machine. By 2029, he predicted, with nanobots coursing through our bloodstreams, wireless neural implants will provide a direct high-bandwidth connection to the brain. And by 2099, he wrote, there will be no longer be "any clear distinction between humans and computers."

2099 is a long way off, but we're striding fast towards the future Kurzweil envisions. One of the first nanotech companies, the Texas-based Zyvex (www.zyvex.com), is already working on a nanotech assembler, a crucial piece of the puzzle. Still, Jim Von Ehr, Zyvex's President and CEO, acknowledges that the work requires patience. "Applications of nanomedicine are years or even decades away, but the incredible size of the opportunity, measured in either lives or dollars, makes it worthwhile," he said.

In the meantime, microtechnology, nanotechnology's big brother, is fast making strides.

Second Sight

Microtechnology works at a micron level, a scale a thousand times larger than nanotechnology—but the promises of the two technologies are ultimately the same. From medicine to manufacturing, both stand to transform the way the world works by providing full functionality at scales smaller than a grain of sand. There's a lot you can do when you're really, really tiny.

And thanks to its larger scale, microtechnology is already an active discipline: Marlene Bourne, Senior Analyst with Cahners In-Stat Group (www.instat.com), predicts that revenues for wireless micro electro-mechanical systems, or RF MEMS, will grow from just over $1 million in 2001 to nearly $350 million by 2006. Just think of the revenues that systems a thousand times smaller than that could attract.

At North Carolina State University, Dr. Wentai Liu is developing a retinal implant, a tiny chip just over four millimeters square, to be implanted on the retina of a blind person. A camera hidden in a pair of glasses transmits visual data wirelessly to the chip—which then responds by stimulating the nerves behind the retina with electrical impulses.

Studies conducted by Liu and by Drs. Mark Humayun and Eugene de Juan at Johns Hopkins University in the late '80s indicated that electrical impulses behind the retina could make a blind person see points of light. Using a limited number of electrodes, Liu explains, the retinal implant is intended to help a blind person make out basic shapes—or possibly far more.

“This is designed for 60 pixels, to provide mobility for a blind person,” he said. “To provide use for reading or facial recognition would probably require several hundred pixels. But the brain has a learning capability, so even when we put 60 into somebody’s eye, once the learning capabilities kick in, the brain might be able to provide reading or facial recognition.”

Liu notes that the principle is essentially the same for a cochlear implant. “There are about 30,000 nerve fibers in the cochlear area, but it only has 16 electrodes,” he said. “After a period of training, deaf people can hear conversation because the brain has fully integrated the cochlear implant: we hope a similar procedure will happen to the blind.”

Smart Dust

The Michigan-based startup Discera (www.discera.com) is working on microtechnology solutions for mobile phones. Replace bulkier components with micron-scale solutions like Discera’s, and you can make the phone cheaper, increase efficiency, decrease battery usage, and fit the phone inside form factors as small as a watch or a pendant.

Dr. Clark Nguyen, Discera’s founder and Vice President, compares the company’s MEMS vibrating resonator devices to guitar strings. “What we’re doing is we’re taking a guitar string that’s 25 inches long, and we’re shrinking it down millions of times to the point where it’s only ten microns long,” he said. Imagine shrinking the whole phone by the same degree, and you can see the potential.

And according to Nguyen, the possibilities really are limitless. “This type of technology makes possible sensor networks, where you can spread them about over a certain area and improve productivity quite a bit—in food production, for example,” Nguyen said. “Or in the office you’re sitting in right now, you could have sensors all over that are monitoring all sorts of things like temperature or humidity.”

Kris Pister, a professor at the University of California at Berkeley, has designed RF MEMS sensors he calls “smart dust motes” which can be used to set up just such a network. In a response to California’s energy crisis in May, more than 50 matchbox-sized sensors were installed in the university’s Cory Hall, monitoring light and temperature conditions throughout the building to help control electricity use.

And in March, a team led by Pister ran a similar test in a military environment, dropping motes from a five foot long unmanned aircraft in the desert. Once placed, the motes were able to detect and track vehicles that passed by, then transmit the data wirelessly back to a base camp. Give them three years, Pister says, and they’ll be able to do the same with millimeter-scale motes and a six-inch aircraft.

Bad Robot

Although the progression to smaller and smaller machines may seem inevitable, it’s not a simple proposition. It would take millions of nanomachines to build anything on a human scale—which means that nanobots are only useful if they can self-replicate. One nanobot produces two nanobots, which produce four, and so on: as they reproduce exponentially, their productive capacity increases as well. And therein lies the danger.

In *Engines of Creation*, Drexler warned that just as a nanobot could turn coal into a diamond, it could do the same in reverse. "Tough, omnivorous 'bacteria' could out-compete real bacteria," he wrote. "They could spread like blowing pollen, replicate swiftly, and reduce the biosphere to dust in a matter of days." Such nano-machinery could also be targeted selectively, focusing on a specific ethnic group or geographic area—and nanomachines, unlike atomic bombs or chemical weapons, will be primarily civilian devices, making them widely available.

In a much-publicized *Wired* cover story last April (www.wired.com/wired/archive/8.04/joy.html), Sun Microsystems cofounder Bill Joy warned of the "Faustian bargain" that nanotechnology demands, suggesting that the only appropriate response is to stop developing it altogether. "Certain knowledge is too dangerous and is best forgone," he wrote.

But Kurzweil, speaking at the recent Fortune Editors' Invitational Conference in Aspen, Colorado, contended that halting progress can't be the answer. "We could scarcely stop the emergence of nanotechnology without relinquishing virtually all technology development," he said. "The dangerous technologies represent the same knowledge as the beneficial ones."

Like nuclear power fifty years ago, nanotechnology promises both boundless opportunity and inconceivable destruction. More than five decades after the Trinity Test, science is once again on the threshold of a technology that carries with it huge responsibility. And this time, we've got hindsight on our side.