INSTANTMAN

Factory in a box: Inside a direct-manufacturing machine (above), custom hearing-aid shells arise from nylon dust, lasers, and digital files. Direct manufacturing is replacing laborious manual techniques (right).

NUFACTURING

From jet parts to hearing aids, the manufacture of finished goods directly from digital files and piles of powder is a growing trend. Someday, retail stores might even print out a product just for you. **BY IVAN AMATO** PHOTOGRAPHS BY MICHEAL MCLAUGHLIN

A boundary line of manufacturing history cuts across the factory floor of Siemens Hearing Instruments in Piscataway, NJ. On one side, skilled technicians use casting techniques, precision tools, and years of experience to craft the acrylic shells of hearing aids modeled from silicone impressions of actual ear canals.

On the other side of the factory floor, two pizza-oven-sized machines create similar shells from nylon dust. Inside the machines, needles of laser light, guided by digital design files, robotically scan back and forth, cinching paper-thin layers of dust into tough strata of plastic. Four hours and several hundred laser sweeps later, a batch of 80 hearing-aid shells is completed *(see "From Dust to Hearing Aids," this page)*. The process saves hours of human labor and produces hearing aids that fit and sound better than traditional ones.

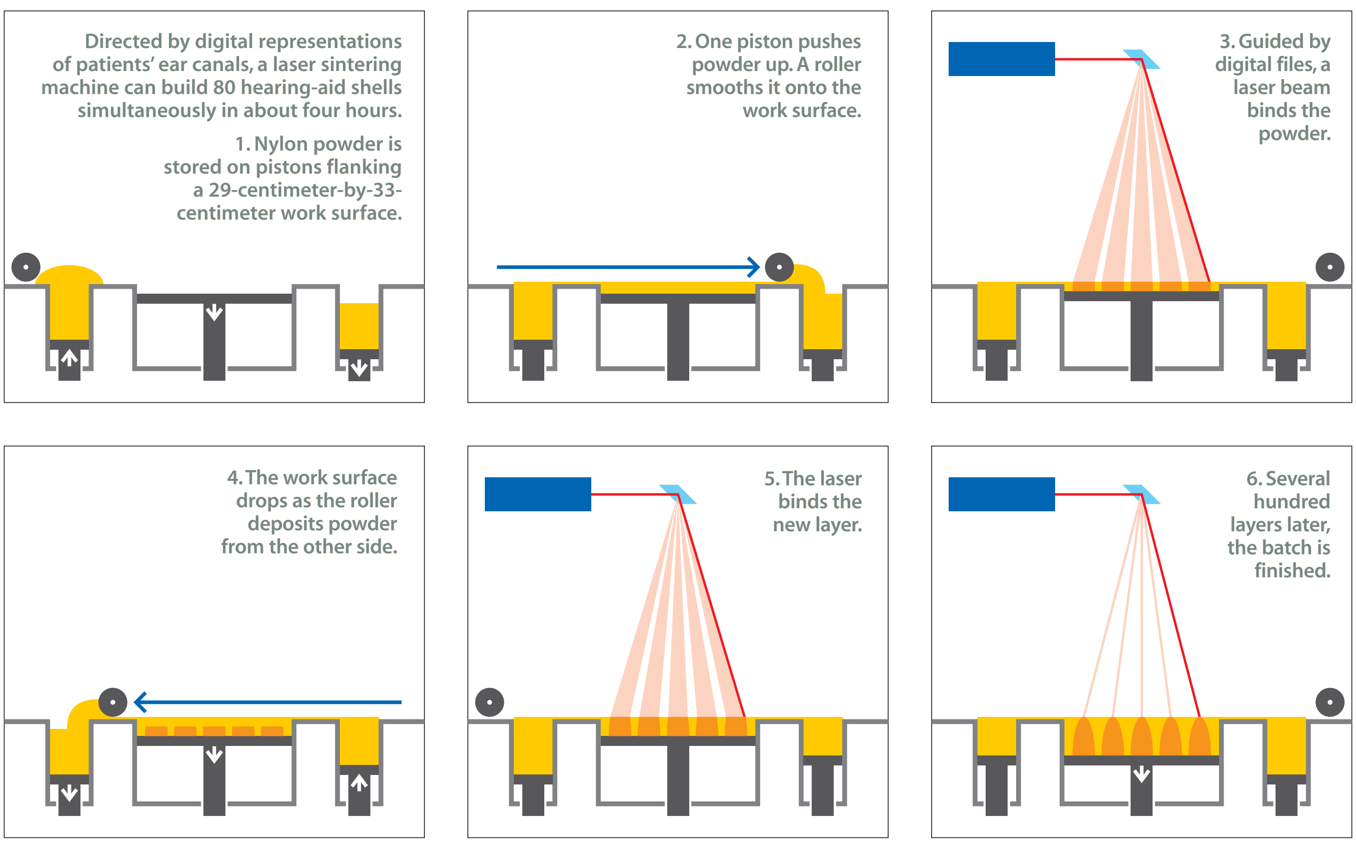
It works so well that Siemens, the world's largest maker of hearing aids, is completely switching to the technology at several factories. "This whole process allows us to be more accurate and eliminate human error. This is going to change the business," says William Lesiecki, director of software and e-business solutions for Siemens Hearing Instruments.

Siemens's switchover is just one example of a surging trend in automated manufacturing. Robotics on the factory floor are, of course, nothing new. These days, everything from cars to pharmaceuticals comes off of heavily automated production lines. But direct-manufacturing machines go the next step, using only a digital file—whether created by an engineer or by a scan of a physical object—to custom-make products. They are, in essence, large three-dimensional printers. They both fabricate materials—for example, plastic or metal from powders, or nylon from resin—and shape them into parts. In short, they're a direct bridge between the virtual world of design and the physical world of manufacturing.

The technology is already beginning to displace conventional manufacturing in some areas, like specialized parts for jets. At On Demand Manufacturing, a Boeing subsidiary in Camarillo, CA, 60 complex tubes for the environmental systems inside fighter jets are printed out by machines similar to those at Siemens. Gone are the expensive, specialized molds and dies that these parts previously required. Gone are stringent limits on shape and design, and the months-long waits for custom parts. It's the wave of the future in aerospace, says Miller Adams, a Boeing vice president at the company's Phantom Works R&D organization. "We could have cost savings of 50 percent on specific parts," he says, easily adding up to millions of dollars per year. What's more, printing parts compresses manufacturing schedules by 50 percent as well. "We believe this will work for many industries outside aerospace," Adams adds.

Indeed, Siemens and Boeing are not alone: more and more companies are exploiting direct manufacturing, says computer scientist David A. Bourne, director of the rapid-manufacturing laboratory at the Robotics Institute of Carnegie Mellon University. Bourne says direct manufacturing will eventually become ubiquitous in the manufacturing sector. "I've been talking about this for 15 years, and now it's becoming real," he says. "In

FROM DUST TO HEARING AIDS



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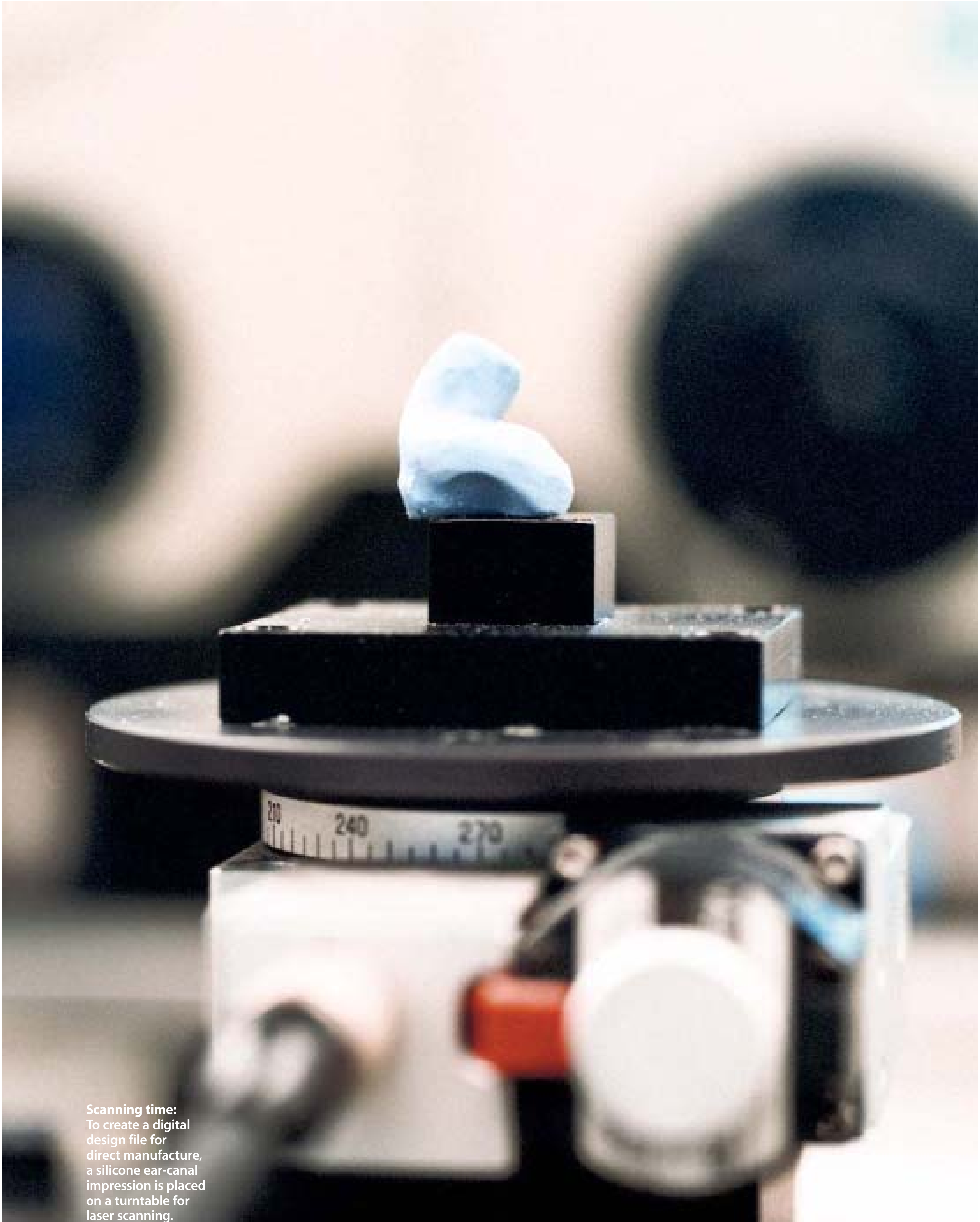


Scanning time: To create a digital design file for direct manufacture, a silicone ear-canal impression is placed on a turntable for laser scanning.

five years, it will be on most people's lists of the coolest technologies." Among the business benefits, he notes, will be the dramatic reduction or even elimination of costly overstock. Companies will only have to make products when "someone is standing there with a dollar bill to pay for it," he says. Then, the manufacturer will simply print one out.

For now, the examples of these printout products are somewhat arcane. Beyond hearing aids and jet ducts, they include electrical boxes for race cars, fine-mesh ceramic filters used in making soy sauce, and surfaces that guide air inside jet engines. But evidence of surging interest is unmistakable, says Terry Wohlers, an industry analyst in Fort Collins, CO. The number of machines doing rapid prototyping—a key progenitor of direct manufacturing—is approaching 10,000, and a small but growing percentage of these machines are now being used for direct manufacturing.

Breaking out: Pieces of replacement bone, complete with micropore structures, emerge from an ink-jet printing process.

Of course, not everything can be made with such machines, and nobody expects them to become as ubiquitous as laser printers: for one thing, the cheapest ones now cost around $30,000 *(see "You Want One of Your Own?" p. 62)*. Direct manufacturing works best for relatively low-volume fabrication of high-cost items. Still, that describes multibillion-dollar markets in arenas as diverse as aerospace, medical devices, and even human bone replacement. "This will be a completely different way of doing things," says mechanical engineer Joseph J. Beaman of the Laboratory for Freeform Fabrication at the University of Texas. "You just push a button."

Boning Up

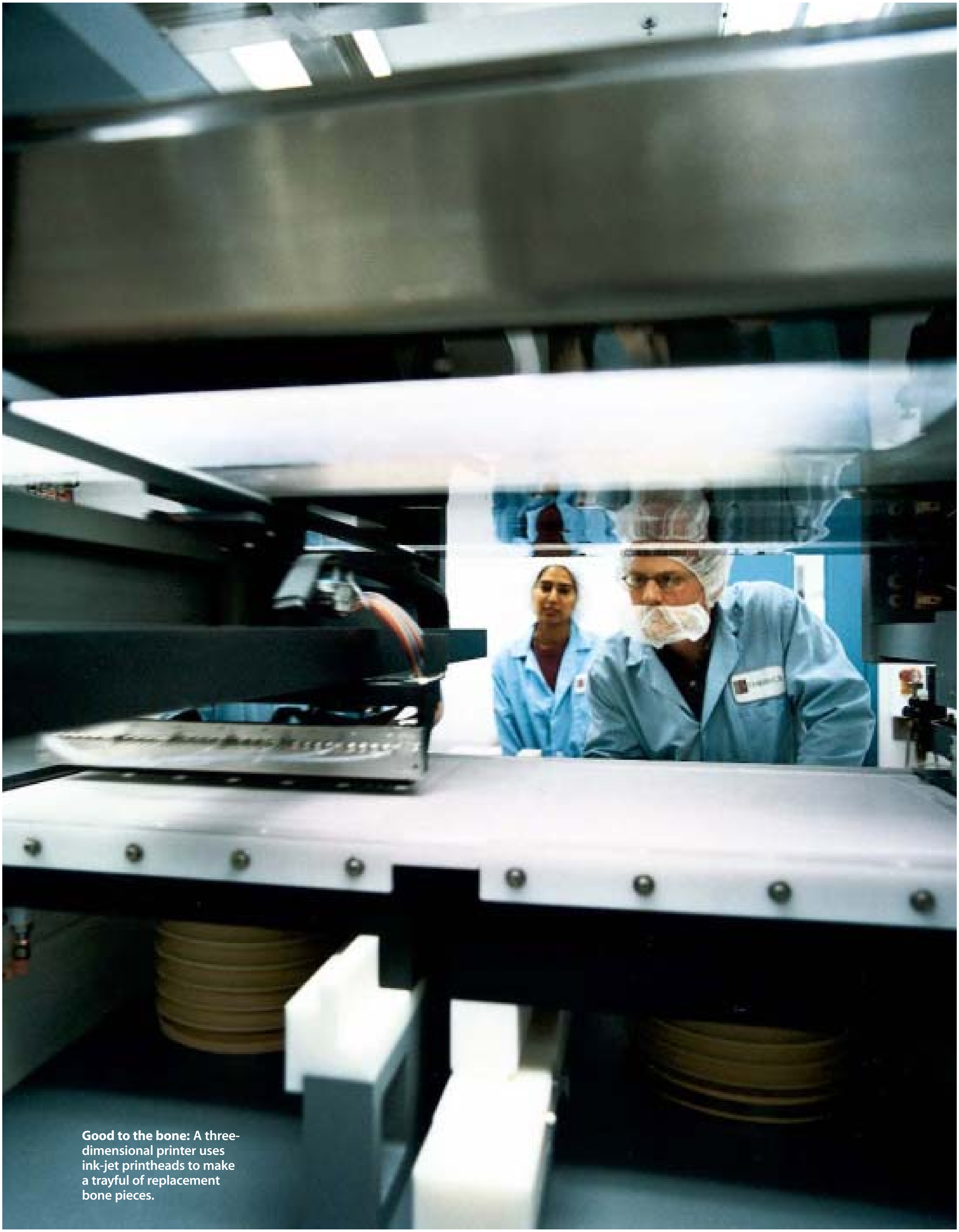
In some ways, direct manufacturing is a natural consequence of the relentless pressure to reduce the time it takes to move a product from concept, through design and development, to commercial reality. When computer-aided design and digitally controlled tools began infiltrating factories in the 1970s and 1980s, the stage was set for rapid prototyping, which uses printing technologies to create three-dimensional objects that serve as prototypes for, say, toys or car parts. With prototypes in hand in just hours—rather than the weeks or months hand-carving and casting once took—designers can more quickly refine products, and engineers can quickly detect and correct problems.

The first rapid-prototyping machines used lasers to bind successive layers of a liquid polymer—a process called stereolithography. Later versions used a broader range of raw materials, such as powders that would fuse together when hit by a laser beam. Another leap came in the 1990s, when the method expanded beyond lasers to include printheads that spewed binding liquids onto powders, adding speed and an even greater variety of materials *(see "Players in Direct Manufacturing," this page)*. At the same time, the push was on to develop these technologies to the point that they could make finished products, not just prototypes. "In the late 1980s, stereolithography had just come out, and it was very inspiring to see," says Emanuel Sachs, a mechanical engineer at MIT who developed the printhead method. "What I set out to do was to shift the focus from making prototypes to creating functional parts directly."

That goal has now been met. On a recent day at the Therics laboratory in Princeton, NJ, two employees in cleanroom suits watched as a car-sized printer made 300 two-centimeter-long chunks of substitute jaw bone. A linear array of eight printheads swept over successive layers of a powder called hydroxyapatite (the major mineral in natural bone), selectively dispensing tiny droplets of an organic binding liquid that would later be burned out during a furnace treatment. Under the relentless sequence of droplets—800 per second—the otherwise formless mass of powder began to take shape. The U.S. Food and Drug Administration approved Therics's bone substitute in late May, and while it hasn't yet been used in an implant in humans, it is already in the hands of surgeons who intend to test it soon. As

PLAYERS IN DIRECT MANUFACTURING

COMPANY	TECHNOLOGY	APPLICATIONS
3D Systems (Valencia, CA)	Selective laser sintering machines that use lasers to bind plastic or metal powders; stereolithography systems that cure liquid resins with laser-generated heat	Medical implants and prosthetics, military-jet components, hearing aids, Formula 1 race car parts
Stratasys (Eden Prairie, MN)	Heated plastic expelled by moving nozzles	Pump parts and small gears
Therics (Princeton, NJ)	Three-dimensional-printing technology, in which arrays of printheads spray droplets of organic binders onto powders	Bone substitutes with the porosity needed for cells to take hold after implantation
On Demand Manufacturing (Camarillo, CA)	The use of 3D Systems' sintering machine to create high-strength parts	Aircraft ductwork and other custom plastic and metal parts for aerospace applications
Siemens Hearing Instruments (Piscataway, NJ)	The use of 3D Systems' sintering machine to manufacture custom-fitted hearing-aid shells	Hearing-aid shells
Z (Burlington, MA)	Ultrafast three-dimensional printer that uses proprietary powders	Full-color geographical models for military planning



Good to the bone: A three-dimensional printer uses ink-jet printheads to make a trayful of replacement bone pieces.

a means of making replacement bone, direct manufacturing has some advantages. Say an accident victim has lost a fragment of arm bone. The piece can be digitally reconstructed using images of the same bone on the other arm. What's more, the printing technology is able to create pores just 50 micrometers wide, which allow the bone segment, once implanted, to host real cells that make real bone, strengthening and eventually supplanting the implant.

The FDA's approval of Therics's directly manufactured bone substitute is a milestone for the manufacturing technology. Indeed, Ranji Vaidyanathan, a materials scientist at Advanced Ceramics Research in Tucson, AZ—which is developing its own printed bone substitutes—expects directly manufactured bone to be common in three to five years. "I would say it will change the way we look at replacement bone," he says.

Testing the metal: These prototype rocket engine parts were made by laser-binding metal alloys, then baking them in a furnace.

Custom Robots

Bone implants presage far broader future applications that will follow improvements in speed, precision, and variety of raw materials. On Demand Manufacturing, which already makes plastic and metallic parts, hopes to offer materials that can perform under the most demanding of conditions, including the furnacelike heat of a rocket engine. The company has developed superalloy powders that can be shaped via direct-manufacturing machines and then baked into complex, superstrong turbine parts. The company is now taking the steps required to qualify the components for use in rockets.

Direct-manufacturing technology is going mobile, too. In a move that might one day have consequences for your local auto garage, the U.S. Army is developing truck-sized mobile units that can fabricate replacement parts—based on digital files or on-the-spot scans—for vehicles and weapons right on the battlefield.

And some are pushing the technology into the realm of robotics and electronics, complete with moving parts. As a first step, John Canny, Vivek Subramanian, and their colleagues at the University of California, Berkeley, are experimenting with ink-jet printing as a method for shaping organic semiconductors and electroactive materials into smart components that change shape in response to a voltage. One long-term vision is an all-polymer custom robot weighing less than one kilogram that could be printed for specific jobs, like fixing wiring in a tight spot on an airplane. But the Berkeley researchers' initial goals are more modest; Subramanian says they expect to build their first demonstration widget—perhaps a small movable joint—within two years.

The technology could eventually go retail, too. John Wooten, general manager of On Demand Manufacturing, envisions something like a chain of three-dimensional Kinko's equipped with direct-manufacturing equipment that could replicate pretty much any object that could be scanned or defined in a digital file. "It's possible to envision a guy with his '65 Mustang and a broken window handle going there to have a new handle made," Wooten says. In a similar vein, Carnegie Mellon's Bourne foresees new options in personal customization: cell phones, CD players, and all kinds of consumer products with shapes and colors specified by customers.

While these retail applications are still hypothetical, businesses are sprouting to serve manufacturers on a contract basis. Companies like Accelerated Technologies in Austin, TX, and Met-L-Flo in Geneva, IL, accept digital design files and make rapid prototypes—a concept that could evolve into custom-printing products for retail customers. If such a service does materialize, a neighborhood car restorer looking to duplicate a tiny piece of grillwork, or a homeowner replicating old trim, would find it akin to a digital Home Depot, with an infinite virtual stockroom of customized products. TR

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YOU WANT ONE OF YOUR OWN?

IN ALL LIKELIHOOD you own a laser printer, which would have been an extravagance 18 years ago. Does this mean a personal fabricator is on its way to your home? You'd scan in something that catches your eye—or download a digital file from the Internet—then hit the "print" button, and your fabricator would bind, glue, and otherwise mold a material into a cell-phone cover, custom-designed fork, action figure, or any number of other digitally definable three-dimensional objects.

Don't hold your breath. Most industry watchers still consider such a scenario a long way off. Earlier this year, no less a player than printer giant Hewlett-Packard floated the concept of a less-than-$1,000 device that could create three-dimensional objects from digital files. More recently, though, the company drew back from the idea. "All I can say is it's one of the things we are looking at. I can't say whether we are still looking at it or have abandoned it," said Dave Berman, an HP spokesman.

Indeed, direct manufacturing's trajectory to homeowner affordability looks long. Prices of industrial machines have dropped quite a bit, but the cheapest still cost $30,000. Even if prices drop below $10,000 in the next decade, predicts Terry Wohlers, an industry analyst in Fort Collins, CO, the most likely buyers of household replicators will be self-employed engineers, who could make prototypes in their home offices, and tinkerers who already have garages full of machine tools. A killer app for the home is hard to foresee. "Most people wouldn't be able to justify a $10,000 or even a $1,000 price tag," Wohlers says.

But for those who did take the plunge, their children might someday pull CDs off of cereal boxes and print out action figures from the latest movie blockbuster. Add the Internet to this scenario, and they'd e-mail handmade presents to friends—or at least to those with their own personal replicators.