of engineering to manufactured parts."

David Bolognino, director of General Motors' design fabrication operations, says that additive manufacturing tools in the company's design labs are used to produce automotive parts for preproduction models of the Chevrolet Volt, GM's first all-electric vehicle. The technology "allows us to do very quick iterations of complicated parts and systems with supreme accuracy to reduce product development time and expense," says Bolognino, who recalls seeing his father go from hand-chiseling wooden prototypes to becoming an early advocate of and a supervisor in GM's rapid prototype lab. Bolognino says traditional tooling methods are still required for car manufacturers like GM to meet their mass-production needs: "At the end of the day, we have to be careful not to make parts that can't be tooled in other ways," he says.

Made in space

Manufacturing in zero gravity is the latest venture for 3D printers. In July the entrepreneurs at Made in Space, a Silicon Valley startup, successfully demonstrated the 3D printing of a plastic adjustable wrench during a NASA parabolic airplane flight. Jason Dunn, the company's chief technology officer, says they still have much to learn about the fluid dynamics of the process in space. Once those problems are solved, Dunn says that a space-bound vehicle would be lugging less weight because its cargo could be built in space using up to 30% less raw material. On Earth, satellites and other space equipment are made artificially heavy to withstand extreme liftoff vibrations. Dunn and his business partners are currently preparing their customized 3D printer for performance test flights funded by NASA's Commercial Reusable Suborbital Research program aboard manned spaceflights expected to start next year (see the report about the NASA program in PHYSICS TODAY, October 2010, page 28).

Revenues from additive manufacturing technologies grew by 24.1% in 2010, according to the latest *Wohlers Report*, an annual state-of-the-industry publication by Wohlers Associates. The report highlights the "explosive growth of low-cost personal 3D printers," which are primarily sold to individuals, small businesses, and academic institutions. The personal systems start at around $1000 and are used for materials science research, basic prototyping, and teaching; industrial machines can cost more than $1 million. "I'm thrilled by how many universities, community colleges, even high schools, are buying the technology," says Wohlers.

"Kids are empowered to learn math and science when they can use a 3D printer to design an iPod holder for their bike," says Hod Lipson, a mechanical engineer at Cornell University's computational synthesis laboratory. He and his team use 3D printers to fabricate tiny, bio-inspired, battery-powered flying robots, dubbed ornithopters, which mimic the aerodynamic properties of hovering birds and insects. "Just a few years ago, 3D printing was an expensive technology that only large design firms could afford," says Lipson. "Now [it is] like pencil and paper in the modern robotics lab. If we need a component, we can print it within minutes."

Clay versus Lego

Lipson and Gershenfeld say that 3D printing is just the start of the digital fabrication revolution. They are collaborating on the development of programmable materials, which Gershenfeld describes as "coded construction." Their aim is to mimic the efficiency of molecular biological processes by applying computational error-correction techniques. "The difference between bulk raw materials and digital materials is like the difference between playing with clay and playing with Lego blocks," Gershenfeld says. Lipson adds that the ability to assemble materials with such precision could lead to robots and machines that "respond to external stimuli in a much more sophisticated way."

Jermey N. A. Matthews

Electron microscope gets x-ray vision

A new electron microscope makes possible direct imaging and identification of individual atoms via x rays. Anticipated applications of the Austrian scanning transmission electron microscope (ASTEM) include analyzing material interfaces and impurities in semiconductor devices, and studying nanoplasmonics. With improved sample preparation methods the instrument could eventually be used to study biomaterials, says Ferdinand Hofer, director of the Austrian Center for Electron Microscopy and Nanoanalysis in Graz, where ASTEM was inaugurated on 22 June.

The electron microscope's resolution of 70 pm (a picometer is 10^{-12} meters) is not the world's best; that distinction goes to a 50-pm-resolution instrument at the National Center for Electron Mi-

AUSTRIAN CENTER FOR ELECTRON MICROSCOPY AND NANOANALYSIS

The Austrian scanning transmission electron microscope at its unveiling this summer.

croscopy in Berkeley, California. What ASTEM does offer, says NCEM director Ulrich Dahmen, is a "highly sensitive, large-angle x-ray detector that puts the instrument at the forefront of fine-probe x-ray spectroscopy."

In an electron microscope, images are produced via elastic and inelastic interactions of electrons with the sample. In ASTEM, the x rays come from atoms relaxing after core electrons get ejected by incident electrons. Analyzing x rays "has the big advantage that it's easily possible to detect almost all elements of the periodic table," says Hofer. "If we see dots that correspond to atoms, we can say if they are sulfur or iron or oxygen." Understanding chemical composition on the nanoscale is becoming more important, he notes, "because components are shrinking. And we need better resolution to see more details, and the details influence material properties." ASTEM also opens new possibilities, he adds, by combining x rays with three-dimensional characterization of samples via electron tomography.

Three components give ASTEM its muscle, says Hofer. One is a lens system to correct for image blur caused by spherical aberration. (The Berkeley instrument achieves superior resolution mainly because it also addresses chromatic aberration.) The others are a very bright electron source and a "clever incorporation of x-ray detection," Hofer says. The detection system is a variation on conventional energy-dispersive x-ray spectroscopy. The electron source and the x-ray detector are proprietary technologies developed by FEI, an electron-microscope company in the Netherlands; the company claims its electron source generates up to 5 times more x rays than other sources and that its wide-angle Super-X system increases collection by a factor of 10. "When we heard about FEI's x-ray detection system," Hofer says, "we thought we would cooperate with them. They need the feedback."

Much of the €4 million (nearly $6 million) tab for ASTEM was shelled out by companies. About one-third of the user time will go to industrial research projects, Hofer says, with the rest for basic science. Raimund Förg, a physicist at the German semiconductor company Infineon, says, "We collaborate with [the Austrian center] because we need a fallback to do high-risk research in a near-industrial atmosphere."

Förg says Infineon's first interest in ASTEM is the higher resolution the new instrument offers. But in a few years, he says, he can imagine using the atom-identification aspect of the instrument to look, for example, at interlayers of graphene. "Graphene grows epitaxially, so it's very important to know the surface. And when you do atomic resolution, you get more information about functionality, and you can influence it."

Toni Feder