Breakthrough Factories

Manufacturing's pivotal role in nurturing innovation is being recognized from China to California. Where—and how—is it being done best?

The Big Question

Making Innovation

The hubs of advanced manufacturing will be the economic drivers of the future because innovation increasingly depends on production expertise.

Visitors to the Crosspointe Rolls-Royce facility in Prince George County, Virginia, have to don safety glasses and steel-tipped shoes, just as they would at any traditional factory. But then things start to look different. Past the cubicles filled with programmers and support staff sits a 140,000-square-foot factory with spotless white concrete floors, bright lighting, surprisingly quiet equipment, and very few human beings.

Opened in 2011, Crosspointe is the kind of factory that makes a good backdrop to a political speech about advanced manufacturing, as President Barack Obama knew when he arrived less than a year later. It’s global: the U.S. operations center of a U.K. company, it uses titanium forgings from Scotland, Germany, or the United States; shapes them into fan disks; and, after milling, polishing, and...
testing, ships them off to England, Germany, or Singapore. Once there, each disk will become one of 10,000 parts in a typical engine.

It’s also highly automated: $1.5 million machines made by DMG Mori Seiki do the initial milling of the disks, following steps directed by Siemens software with a minimum of human interference. On a day in early summer, eight machines were being monitored by three operators. Computer screens in front of the machine displayed instructions in pictures and text, flashing warnings when a part has not met specs or the machine needs to be serviced. Later an automated measurement machine with a probe on the end would spend eight hours inspecting 1,000-plus distinct dimensions of the part. For the next 25 years, Rolls-Royce will keep data on each part, starting with exactly how it was made. Sensors in the engine will track how the engine and its parts are holding up, and maintenance and flight data will be carefully recorded.

It’s not just pristine floors, scarce workers, and a global network that make Crosspointe emblematic of manufacturing today. It’s also the ecosystem surrounding the facility. Just down the road is the Commonwealth Center for Advanced Manufacturing, a research center whose members include Airbus, NASA, and the University of Virginia.

There, Rolls-Royce staff who know the challenges and details of manufacturing work with researchers and suppliers to improve the factory and its products, says Crosspointe manufacturing executive Lorin Sodell. “Often a great idea for a new manufacturing process won’t ever make it into production because that connection is missing.”

Most of the advanced machining and other innovative processes in place at Crosspointe were developed and first tested at a similar research center near the company’s plant in Sheffield, U.K., called the Advanced Manufacturing Research Center. Sodell is already working with suppliers housed in the Virginia research center to diagnose and quickly address new tooling issues and any other problems that might arise.

To understand why manufacturing matters, we must lose some misconceptions. First, manufacturing no longer derives its importance primarily from employing large numbers of people. As software drives more of the manufacturing process, and automated machines and robots execute much of it, factories don’t need as many workers.

Second, the idea popularized in the 1990s and 2000s that innovation can happen in one place (say, Silicon Valley) while manufacturing happens in another (such as China) is not broadly sustainable. If all the manufacturing is happening in China, these networks are growing there, meaning eventually all the innovation—or at least a lot of it—will be happening there too.

Manufacturing will make its most essential economic contribution as an incubator of innovation: the place where new ideas become new products. Thanks to advanced manufacturing technologies, that place can in theory be pretty much anywhere. Robots, software, and sensors work no matter what language is spoken around them. In practice, however, advanced manufacturers thrive best in an ecosystem of suppliers and experienced talent. For this reason, specialized manufacturing networks have taken hold in many regions. Among the success stories highlighted in this report are China’s dominance as a manufacturer of consumer electronics, Germany’s lead in precision tooling and robotics, the United States’ strength in aerospace and car manufacturing, and its role in pushing forward important new manufacturing technologies.

Innovative manufacturing today requires as its base that manufacturers and their suppliers build strong relationships and share knowledge extensively, says Mark Muro, a senior fellow at the Brookings Institution.

China’s achievement is especially significant. Today, it would be nearly impossible for any other region to replicate the country’s manufacturing prowess in electronics or the speed with which its companies can introduce new products, says Harvard Business School professor Willy Shih, a longtime executive at IBM, Eastman Kodak, and other multinational firms who studies the links between manufacturing, product development, and innovation.

It’s not a new idea that manufacturing and innovation are linked. Seventy percent of industrial research and development spending in the U.S. comes from the manufacturing sector. Some have
been skeptical, however, that innovation requires manufacturing know-how.

Apple, for example, has thrived with a system of designing its products in California but having them assembled in China using digital design and manufacturing instructions. That arrangement, printed on the back of every iPhone, has been popular with investors who appreciate not only Apple's wildly successful products but also its “asset light” structure and relatively small workforce. “Couldn’t everyone do what Apple did?” says MIT professor Suzanne Berger, who participated in a three-year-long university task force that examined manufacturing in hundreds of global companies and produced the book Making in America. “In a way, the case that motivated our whole inquiry was Apple.”

Apple did not participate in the study, but in time Berger came to see that the company’s case was not so black and white—that even Apple finds links between manufacturing and innovation. Apple owns the automated production machines in the Chinese factories that manufacture its products. Many California-based Apple engineers spend at least 50 percent of their time in China as new products are launched, she learned.

One engineer explained to Berger that it was critical to be on the ground in China for two reasons: to see what problems arose when the products prototyped in the U.S. hit large-scale production, and to “understand where I left too much on the table, where I could have pushed farther with the design.”

After three years of study, Berger is a believer that the United States must continue to manufacture if it hopes to be an innovation leader. She finds evidence that the manufacturing communities for emerging high-tech sectors such as solar and wind energy and batteries are already being built outside the country in places where technical expertise, manufacturing skills, and even plant layouts are quickly pulling ahead.

Without manufacturing, “we lose capabilities in the workforce,” says Harvard’s Shih. “It limits what you are able to do down the line.” — Nanette Byrnes

As a result, manufacturing employment has dropped. Between 1970 and 2012, the proportion of German employment in manufacturing fell by half, to around 20 percent (nearly double the U.S. share).

At Audi’s A3 body shop in Ingolstadt, the robots are roughly equal in number to the 800 employees. They do most of the heavy lifting, welding and bonding, and tediously repetitive testing. To Bernd Mlekusch, head of technology development at Audi, the benefits of automation include much higher productivity and reduced demand for untrained workers. At the same time, workers with more training and greater specialization are increasingly needed, he says. German automotive workers, and German manufacturing workers in general, are already paid significantly more than their American counterparts.

The INTA and group framers machines at Audi exemplify the shift toward automation. INTA, or Ingolstadt automatisierter Anbau, is a fully automated door-assembly process that uses...
components that adjust automatically, and, because of the use of sensors and software to create even smarter factories. The idea is to take the automation in individual processes at a place like Audi’s factory and extend it so that every shipping box, component, and manufacturing station will log and share data, Müller says. Today’s highly automated factories share data mainly within a single process or on a single factory floor—say, between a machine that scans a car to determine its body type and a second machine that selects a tool of the right size for that body type. The government initiative aims to go much further.

The vision is that data from every step of production will not simply pass from one shop to another within a business—such as from Audi’s body shop to its paint shop—but will eventually transit between different partnering companies, optimizing the production process without human input by altering speeds, predicting which components are likely to have been damaged during shipping or tooling, changing the order in which items are built, and reordering parts from suppliers.

Audi’s cars are not entirely built by computers and robots, of course. As I pass by an area where people attach mudguards, rear fenders, and a few other parts, one of the engineers chaperoning my visit explains that some stages of physical production are still worker-intensive, whether because of the size or location of the parts involved or the need to perform certain tasks with a precision that robots aren’t currently able to achieve. So far the robots can’t do these specialized jobs, the engineer explains, but, he adds, “we’re working on it.” —Russ Juskalian

Robotics

How Human-Robot Teamwork Will Upend Manufacturing

Robots are starting to collaborate with human workers in factories, offering greater efficiency and flexibility.

● Sometime in the next couple of years, if everything goes to plan, workers at BMW’s manufacturing plant in Spartanburg, South Carolina, will be introduced to an unusual new teammate—a robot arm that will roll around handing them tools and parts as they assemble the German carmaker’s luxury vehicles.

Once isolated behind safety fences, robots have already become safe and smart enough to work alongside people on a few manufacturing production lines. By taking over tiresome and repetitive tasks, these robots are replacing some
people. But in many situations they are augmenting the abilities of human workers—freeing them to do tasks that require manual dexterity and ingenuity rather than extreme precision and stamina. These robots are also increasing productivity for manufacturers and giving them new flexibility.

BMW introduced robots to its human production line at Spartanburg in September 2013. The robots, made by a Danish company called Universal Robots, are relatively slow and lightweight, which makes them safer to work around. On the production line they roll a layer of protective foil over electronics on the inside of a door, a task that could cause workers repetitive strain injury when done by hand, says Richard Morris, vice president of assembly at the Spartanburg plant. Existing industrial robots could perform this work, and do it much more quickly, but they could not easily be slotted into a human production line because they are complicated to program and set up, and they are dangerous to be around.

While the prospect of increased automation will inevitably cause worries about disappearing jobs, BMW's Morris can't foresee a day when robots will replace humans entirely on the factory floor. “Ideas come from people, and a robot is never going to replace that,” he says.

Still, robots on human production lines at BMW and other manufacturers promise to transform the division of labor between people and machines as it has existed for the past 50 years. The more traditional robots that apply paint to cars, for example, work with awesome speed, precision, and power, but they aren’t meant to operate with anyone nearby. The cost of setting up and programming these robots has helped ensure that plenty of small-batch manufacturing work is still done by hand. The new robots, with their ability to work safely next to human coworkers, let manufacturers automate parts of the production process that otherwise would be too expensive. And eventually, by collaborating with human workers, the robots will provide a way to combine the benefits of automation with those of human ingenuity and handcraft.

Sales of Universal’s robot arms have grown steadily since they first came to market in 2008. Other companies, such as Boston-based Rethink Robotics, are developing similar robotic systems designed to work close to people. Rethink sells a two-armed robot called Baxter that is not only safe but extremely easy to program; any worker can teach it to perform a new task simply by moving its arms through the necessary steps.

The next generation of robots to work alongside humans are likely to be faster and more powerful, making them considerably more useful—but also necessitating more sophisticated safety systems. These safeguards are now affordable because the sensors and computer power needed to react quickly and intelligently to safety risks have become cheap. In the future robots will also collaborate with humans in far more complicated ways—performing the heavy lifting in an installation job, for example, while the human does the necessary wiring.

BMW is developing its next generation of robots in collaboration with the lab of Julie Shah, an assistant professor at MIT who researches human–machine collaboration. The lab is also working with the aircraft makers Boeing and Embraer. “If you can develop a robot that’s capable of integrating into the human part of the factory—if it just has a little bit of decision-making ability, a little bit of flexibility—that opens up a new type of manufacturing process more generally,” Shah says.

Shah is developing ways for robots to interact intelligently with their human coworkers. At ABB, a Swiss energy and automation company, human and robot teammates swap tasks to learn each other’s preferences, resulting in a process that gets the job done more quickly. Shah has also shown that teams made of humans and robots collaborating efficiently can be more productive than teams made of either humans or robots alone. In her experiments, this cooperative process reduced human idle time by 85 percent.

Workers seem comfortable with the idea of robotic colleagues, too. The latest research from Shah’s lab, in fact, suggests that people collaborating with manufacturing robots prefer to let the robot take the lead and tell the workers what to do next. So the robots on the production line in Spartanburg might someday be upgraded from handing out tools to giving instructions on how to use them.

—Will Knight

### High-Tech Factory Jobs

U.S. employment in high-tech manufacturing industries (in thousands)

![Graph showing U.S. employment in high-tech manufacturing industries from 2000 to 2012.](https://example.com/tech_jobs_graph.png)
Jobs

The Hunt for Qualified Workers

Employers have 300,000 unfilled manufacturing jobs.

- Worried that U.S. workers are ill-prepared to work with new manufacturing technologies like 3-D printing and robotics, President Barack Obama has plans for a national program that over the next 10 years would build 45 hubs where manufacturing companies, community colleges, universities, and government agencies can prepare workers for the factories of the future.

The program underlines a growing concern that gaps in workers’ skills will hinder the current renaissance of American manufacturing. Although employment in the U.S. manufacturing sector dropped steadily from 2000 to 2010, manufacturing has added 646,000 net new jobs over the past four years, according to White House figures.

Though many firms are hiring, as of late June, 302,000 manufacturing job openings were unfilled, according to the U.S. Bureau of Labor Statistics. A skills shortage could grow more acute in the next few years. The Boston Consulting Group predicts that by 2020, the United States could face a shortfall of 875,000 highly skilled welders, machinists, machine mechanics, and industrial engineers.

The skills gap seems to be confined to a minority of smaller companies that require specialized skills, according to a 2013 report by MIT’s Production in the Innovation Economy study. The problem is not as pervasive as one might think given how much attention it has received, says Paul Osterman, a professor at MIT’s Sloan School of Management and a member of the commission that conducted the study.

Many of the specialized jobs that manufacturers are having the hardest time filling today involve conventional manu-

Five of the Hardest Manufacturing Jobs to Fill

We compared a list of hard-to-fill jobs from the Manufacturing Institute with a proprietary labor-market data set from Economic Modeling Specialists International, which pulls pay rates and other data from industry and government sources. Manufacturers listed are a sampling of major employers in the metro area where each job is most concentrated.
facturing tasks. Pipe fitters, mechanical engineering technicians, welders, machinists, electronics assemblers, and operators of computer-numeric-controlled machines are among the most needed workers identified in surveys conducted by the Manufacturing Institute, a non-profit research affiliate of the Washington, D.C.–based trade association the National Association of Manufacturers.

As workers retire, it’s becoming harder to find people with these traditional skills, says Ben Dollar, a principal in Deloitte Consulting’s manufacturing practice.

For a smaller number of companies, the priority is getting workers up to speed on the skills they’ll need in tomorrow’s factories. In the last 18 months Siemens USA has donated more than $3 billion worth of manufacturing software to colleges in a bid to help train the next generation of advanced manufacturing workers.

Siemens itself plans to hire 7,000 more people in the U.S. by 2020. Their positions will be related to IT, software development, software engineering, and computer science, says Siemens USA CEO Eric Spiegel. “The digital world is coming, and it’s coming very fast,” he says. “There will be jobs. People may not count those jobs in IT and software development as manufacturing jobs, but they really are related to manufacturing.”

—Kristin Majcher

Case Study

The New Chinese Factory

Leading manufacturers in China combine the country’s historical labor advantages with expertise in automation, design, and manufacturing.

With its medieval canals and carefully preserved downtown, the eastern Chinese city of Suzhou might have been a quiet burgh compared with neighboring Shanghai. But in 1994, the governments of Singapore and China invested in an industrial development zone there, and Suzhou grew quickly into a manufacturing boomtown.

Singapore-based Flextronics, one of the largest global contract manufacturers, built factories there, initially to make small consumer electronics. Those products were relatively simple to assemble in great numbers, making them well suited to China’s then plentiful and inexpensive labor force. But by 2006, labor, land costs, and competition were rising, and Flextronics’ margins were shrinking.

The company refocused its two Suzhou factories on more complex manufacturing, aiming to make higher-priced machines for the aerospace, robotics, automotive, and medical industries. To do so, Flextronics has invested in automation, increasingly precise manufacturing, and improved worker training, all while learning to manage a complicated component supply chain.

Today, these more complex goods make up 72 percent of Flextronics’ Suzhou output. Finished products include printed circuit boards, hospital ultrasound machines, and semiconductor testing equipment so complex each machine requires more than five million parts and retails for $2 to $3 million.

It’s a model the Chinese government has pushed manufacturers to adopt, focusing government investment on advanced industries and boosting R&D spending on science and technology. According to data from the U.S. National Science Foundation, between 2003 and 2012 Chinese exports of high-tech products climbed from just over $150 billion to more than $600 billion, making China the largest exporter of such products in the world. Ernst & Young forecasts that by 2022, the country will produce a third of the world’s electrical goods.

On a recent visit to one of Flextronics’ two Suzhou plants, the increasing use of automation is quickly apparent as an automated trolley delivers parts to workers up and down an assembly line, stopping if someone crosses its path. Nearby an LCD wall panel shows the progress of various items moving through quality testing. In the past, workers ticked off boxes on paper forms and entered the results into computer spreadsheets—a time-consuming process fraught with the potential for errors. Now automated data about progress down the assembly line is collected in real time.

Clients can track the data on apps designed by Flextronics. When there’s a disruption due to anything from delivery problems to labor strikes, another app, Elementum, taps into the extensive Yangtze Delta region supply chain, showing customers alternate scenarios for sourcing parts or rerouting production to any of the company’s 30 other mainland plants.

Such services are part of Flextronics’ push to show customers that after years making goods to the specifications of demanding customers like General Electric and Philips, it has more to contribute. Today Flextronics offers its own design and engineering services, consulting on both finished products and ways to improve the manufacturing process.

Flextronics has sometimes expanded its high-end work by going into business with customers. About four years ago, Steven Yang, general manager of one Suzhou factory, led a company investment in a French firm designing a small robot to be used for university research and, potentially, therapy for children with autism. Working from their prototypes, Flextronics designed a manufacturing process that has in six months delivered 1,400 of the robots, which use sonar and facial recognition technology and can be programmed to listen and to speak.

James She, an operation manager in charge of the robot line, says volume has more than doubled since the initial run in the final quarter of 2013, and he expects orders to rise, especially in Asia, where health care and elder care are fast-growing industries. “The robot can be a member of a family in the future,” She says.

Flextronics has pursued automation wherever it has the potential to reduce labor costs and errors. For example, automated optical testing equipment,
which checks that the circuitry on printed circuit boards is correct before they are installed in other machines, has cut the number of workers on the inspection line from six to two.

But as product cycles speed up, it doesn’t always make sense to make large investments in robots. Humans are still more flexible. “The time you have to spend changing the machine means it’s not always worthwhile to automate,” says Es Khor, an engineering director at the factory. “When we look for where to automate, we also look for process-specific, rather than just product-specific, tasks.”

So while the French robot line may be creating the health-care assistants of the future, at the moment the robots are being assembled by 28 workers wearing navy blue uniform smocks, mostly young men from rural China. All of them have had at least three months of technical training, and the French company provides performance-based bonuses and organized leisure activities in hopes of reducing turnover and retraining costs. Flextronics has also upgraded its dormitories, built worker break rooms, organized hiking trips and choral groups for employees, and staffed counseling hotlines, all with a view to retaining increasingly expensive, and highly trained, labor.

Twenty-year-old Lan Wenzhi has been working on the robot production line for six months. His job is fastening in tiny screws that hold the battery inside a small box. He has a high school diploma, a smartphone, and a fondness for American movies. His monthly average take-home pay after taxes, including overtime, is about 3,500 yuan (about $570). Factory general manager Yang says that with rising wages in this part of China, labor has increased from about 2 percent of the factories’ costs in 2005 to about 4 percent today. But it’s still relatively small when compared with the 80 to 85 percent of the operating budget spent on materials.

For Yang and Flextronics, the goal is to take advantage of nearly two decades of manufacturing experience to make their factories centerpieces of innovation, not just cheap places to make things.

—Christina Larson

Economics

Cheap Natural Gas Boosts Manufacturing

Companies that use natural gas as a raw material find the U.S. an increasingly attractive place to be.

• The fastest-growing slice of the U.S. manufacturing sector today is not being driven by automation or cutting-edge robotics but instead by cheap, plentiful natural gas unleashed by fracking shale deposits.

From 2011 to August 2014, the American Chemistry Council, the trade association of the chemical industry, tallied 196 announcements of new chemical plants or upgrades to existing ones in the United States, with investments totaling $124 billion. Huge petrochemical companies such as Saudi Basic Industries, Dow Chemical, and Chevron Phillips Chemical Company are among the investors. Texas is undergoing the largest expansion of petrochemical manufacturing since the 1960s, and other gas-rich parts of the country, including Pennsylvania and the Ohio Valley, are benefitting too.

“Ten years ago everyone was talking about projects in the Middle East. Now … everyone is talking about investing here in the U.S.” — Fernando Musa, CEO, Braskem America

Samsung Electronics, which operates semiconductor fabrication plants in Austin, Texas, pays close to $60 million a year in electrical bills, says general counsel Catherine Morse, but its recent decision to invest $4 billion mostly in new tooling at the site had nothing to do with electricity prices. Its energy supplier, Austin Energy, relies extensively on solar and wind power, so cheaper gas has a limited benefit for Samsung.

The investment was primarily motivated by an interest in expanding the existing plant’s expertise in logic chips, the chips that control the operation of digital devices. “We do benefit from lower natural-gas prices,” says Morse. “But that’s not driving our investment.”

—Nanette Byrnes
Case Study

Mother Machines

A California factory recently built by Japanese-German firm DMG Mori Seiki makes the case for the future of U.S. advanced manufacturing.

A factory worker drives a forklift carrying a four-ton metal casting across a polished concrete floor. Surrounded by looming robotic equipment, he’s the only human in sight at DMG Mori Seiki’s gleaming machine-tool plant in Northern California.

Three rows of towering, growling machines carve out precision components from rough metal castings weighing anywhere from a few pounds to a few tons. It’s the kind of almost-deserted vista you would expect in advanced manufacturing.

This is the plant’s automated half, but on the other side of a wall with windows, assembly lines swarm with people in white helmets and navy uniforms. There, 40 workers build bedroom-size machines by hand, assembling 2,000 parts to create the computer-driven instruments that will form the hearts of auto, aircraft, and electronics factories across America.

The Japanese call them “mother machines,” because they make other machines possible. Also known as milling machines, they use spinning tools to carve complex shapes out of roughly cast pieces of metal. The results include molds for die casting, gears for transmissions, and cases for smartphones.

The Davis factory builds some of the most advanced computer-numeric-controlled (CNC) milling machines in the world. Fast, durable, and accurate to the micrometer, they are able to move both the cutting devices and the parts they’re shaping in multiple directions. Manufacturers can use DMG Mori tools to make more products, make them faster, and use less energy over longer periods of time.

The quality and productivity of the Davis machines put them “at the upper end of the industry,” says David Dornfeld, chair of the mechanical engineering department at the University of California, Berkeley.

DMG Mori’s decision to build the $50 million factory in Davis says important things about the future of U.S. manufacturing, according to Dornfeld. As automation makes labor costs less important, producers of everything from smartphones to artificial knees to electric cars are increasingly able to choose local production, he says.

Among the key advantages of locating in California: the factory is closer to customers—not trivial when shipping products that weigh tens of thousands of pounds—and to the company’s innovation center and local university research partners. Building some of its machines in the United States also insulates the company from losses on currency exchange and has helped to improve its sales, profits, and share of the U.S. market. The United States now accounts for 25 percent of DMG Mori’s global sales.

The tidy white-and-gray DMG Mori plant sits unobtrusively next to Interstate 80. Flatbed trucks carrying its 20,000-to-40,000-pound products can take the road west to Silicon Valley or east to auto, aircraft, and oilfield-equipment factories.

A map in the assembly hall sprouts tiny white, yellow, navy, and orange flags representing the products’ destinations.

The factory grew out of a relationship between the company and the engineering school at the University of California, Davis, according to Zachary Piner, general manager of the plant’s technology department. The company established its Digital Technology Laboratory in Davis in 2000. Piner and the factory’s managing director, Adam Hansel, were completing graduate degrees when they were hired as two of the first four employees.

Days needed to make a DMG Mori Seiki milling machine

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China's Future Bet

New financial investment in clean energy technologies (in billions of dollars)

“For this combination of software, hardware, and precision manufacturing, companies need proximity to educational infrastructure,” says Enrique Lavernia, the dean of the Davis engineering school. “This high-value manufacturing of sophisticated technology is an opportunity for us in this country.”

One reason for placing the factory on the same site was to capitalize on this talent, Hansel says. With more than 60 engineers, the center designs machine tools and software for DMG Mori worldwide. One smartphone app they designed enables customers to monitor their machines, displaying red, yellow, and green lights next to tiny images of the devices to show their operating status.

The laboratory’s engineers also helped design and set up the factory itself, inventing fixtures for use in product assembly and developing software for the automated lines. Now the laboratory uses the factory to test next-generation prototypes.

Inside the plant, steel-reinforced floors are 40 inches thick to prevent vibrations. The air is almost odorless and free of dust, an enemy of precision and a safety hazard as well. There’s so little noise that people can converse without raising their voices.

Two workers operate a crane to load castings onto the machining sys-
tem. Six hours later, the parts emerge with precise grooves, tracks, threaded bolt holes, and other shapes carved into them. A system designed by the Digital Technology Laboratory uses yellow robotic arms to vacuum up metal shavings and chips.

Machines verify quality at every step. As parts enter the assembly hall, they go through a $1 million coordinate-measuring station that’s accurate to within four micrometers.

The factory goes months without a quality problem, Hansel says. Half of the factory’s products go to small parts-making shops with 50 workers or fewer. They can’t afford malfunctions on machines that anchor their production and cost $120,000 to $500,000. White-shirted quality-assurance workers conduct 100 hours of rigorous tests at various stages of assembly, Hansel says.

Starting with the foundation casting, workers attach major subassemblies that hold the moving parts. They add electrical controls and wiring, hydraulic pumps and piping, and sheet-metal covers. From start to finish, the whole process takes 14 days. There are usually 30 machines under construction at a time.

On one machine, Jeff Gagne installs a shiny rotary table machined on the other side of the plant. He connects the electrical controls and uses sensors to verify that the table is square to the machine’s spindle, which spins cutting tools.

Like the other assemblers, Gagne rolls a cart with a rack of hand tools from machine to machine. There are torque wrenches, box-end wrenches, socket wrenches, and Allen wrenches. Small abrasive stones that can shave off tiny layers of metal are there, too. “About 20 strokes will remove a micron,” Hansel says. “There’s an art to it.”

The DMG Mori plant has about the right balance between automation and assembly by hand, UC Berkeley’s David Dornfeld believes.

“It would be crazy to try to build a machine tool with robots,” he says. “This is instrument-making, and each machine does have its own personality.”

—Robert L. Simison

### Technology

#### How to Build 3-D Printing

One of the most promising new manufacturing technologies still faces big hurdles.

- **3-D printing**—or additive manufacturing, as it is sometimes called—builds parts by depositing layers of metals, thermoplastics, and even ceramics in a design dictated by a computer file. The technology, which can create complex things that are difficult to manufacture traditionally, has been used to print highly customized products like hearing aids and parts for airplane engines.

> It is already well accepted by a few companies. Align Technology uses it to make Invisalign dental braces designed for individual patients, and the aerospace industry uses additive manufacturing to create some high-tech parts. General Electric, one of the world’s largest manufacturers, has developed a 3-D-printed fuel nozzle made from a mix of cobalt, chrome, and molybdenum. Included on our 2013 list of 10 Breakthrough Technologies, it has fewer parts and is 25 percent lighter and five times more durable than previous nozzles, the company says.

But beyond these few early adopters, the technology’s appeal has been limited by its high cost and slow speed. For 3-D printing to become more widely used, the overall process will need to be cheaper, and the machines will need to be redesigned to make it faster and support a wider array of materials.

> “It is still a market that is quite expensive,” says Dominik Rietzel, an additive-technologies specialist at BMW Group Research and Innovation Center in Munich. While 3-D printing can save on the amount of material needed to make a part, preparing and formulating materials for the machines can be expensive, and the results are not always consistent. As a result, traditional injection molding remains more economical for high-volume part production, says Rietzel.

BMW, which has invested substantially in 3-D-printing metals and plastics since buying its first additive-manufacturing machine in 1989, uses the technology for rapid prototyping and to validate manufacturing processes for new car designs, not to mass-produce parts. The cost of the machines and materials would need to be reduced “significantly” before the company would consider that, according to the automaker, which made more than two million cars last year.

Researchers are working to reduce the expense of getting bulk metals and plastics into a form that can be processed with a 3-D printer. Others hope to find ways to eliminate the need to change their form.

Metalysis, based in Rotherham, U.K., says it has developed a way to significantly reduce the cost of 3-D printing with titanium, which is valued for its light weight and strength. Unlike traditional machining, which can use titanium in its natural state, additive manufacturing requires the metal to be turned into a powder. That process is expensive. Using a method based on research from the University of Cambridge, Metalysis is able to create titanium powder for as little as 25 percent of the cost of the usual process.

The U.S. Department of Energy’s Oak Ridge National Laboratory, in Tennessee, is working to develop a machine that can print with high-performance plastics already commonly used in traditional manufacturing. A gantry-style machine, which could be commercialized as early as 2015, uses thermoplastic pellets reinforced with glass and carbon fiber. Widely used in the injection molding industry, these pellets cost just $1 to $10 per pound, and the Oak Ridge printer can use them to produce things as diverse as affordable tooling and unmanned aerial vehicles. There is an added benefit: testing has shown that putting these materials through an additive-manufacturing process actually...
makes them stronger and stiffer by aligning the carbon fibers, says Lonnie Love, a research scientist at the lab.

Besides cost, speed is another obstacle 3-D printing must overcome to be useful in mass production. The systems still generally make parts at only about one cubic inch per hour, says Love, which means it could take days or weeks to make a part the size of a shoebox. But the new machine from Oak Ridge will be able to print parts 200 to 500 times faster. The downside: the surface finish suffers, and parts must go through a traditional machining process to give them their final look.

Google’s Project Ara, which plans to print customized cell-phone parts by 2015, is also pushing for speed. Its supplier, 3D Systems, the first maker of a commercial 3-D-printing machine, has rethought its basic approach. Its new printing process involves an assembly line on which parts move around a track and are built up by fixed print heads above. 3D Systems says this approach has already beaten injection molding speeds.

Beyond speed and cost, manufacturers face one more challenge: perfecting the composition of the materials to give them the strength and versatility needed for industrial applications. NASA’s Jet Propulsion Laboratory in Pasadena, California, working with the California Institute of Technology and Pennsylvania State University, is using lasers to melt metal powders to form alloys that are then deposited onto a rotating rod layer by layer. The process could allow manufacturers to switch between two different alloys during production and make parts from more than one metal.

“We’re learning how all the interactions of machine and material play together, how they form not only the shape but also the properties,” says Christine Furstoss, GE’s manufacturing and materials technology director.

“Forming the properties at the same time you’re making a shape—it’s something that took the forging and casting industry decades to figure out,” Furstoss adds. “We’re trying to do it in years.”

—Kristin Majcher

### The Growing Business of Additive Manufacturing

Companies have been using additive manufacturing since the 1980s, mainly to make prototypes for testing. But in recent years the machines have been churning out an increasing number of functional products and parts. Analysts expect the market for additively manufactured parts and products—and the market for the materials needed to make them—to continue growing quickly.

#### Growth in 3-D Printed Products

The percentage of revenue generated from sales of additive manufacturing machines, materials, and services for making products and parts, rather than for making prototypes, models, and tools.

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</tr>
</thead>
<tbody>
<tr>
<td>Motor vehicles</td>
<td>0%</td>
<td>5%</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>25%</td>
<td>30%</td>
<td>35%</td>
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<tr>
<td>Aerospace</td>
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<tr>
<td>Medical/dental</td>
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<tr>
<td>Industrial/business machines</td>
<td>18.5%</td>
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<tr>
<td>Consumer products</td>
<td>12.3%</td>
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<tr>
<td>Industrial/medical</td>
<td>9%</td>
<td>12%</td>
<td>15%</td>
<td>18%</td>
<td>21%</td>
<td>24%</td>
<td>27%</td>
<td>30%</td>
<td>32%</td>
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<tr>
<td>Academic institutions</td>
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<td>10%</td>
<td>12%</td>
<td>14%</td>
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<tr>
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<td>14%</td>
<td>16%</td>
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<td>Government/military</td>
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<td>4%</td>
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<td>9%</td>
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<td>11%</td>
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<td>Other</td>
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<td>3%</td>
<td>4%</td>
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</table>

**Market value of 3-D printed parts**

- $0.644 billion in 2012
- $1.07 billion in 2013

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### The Materials Market

<table>
<thead>
<tr>
<th>Material Type</th>
<th>2013</th>
<th>2025 Projection</th>
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<tbody>
<tr>
<td>Inkjet materials</td>
<td></td>
<td></td>
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<tr>
<td>Metal powders</td>
<td></td>
<td></td>
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<tr>
<td>Thermoplastic powders</td>
<td></td>
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<tr>
<td>Solid thermoplastics</td>
<td></td>
<td></td>
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<tr>
<td>Photopolymers</td>
<td></td>
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</tbody>
</table>

Source: Wohlers Associates

Source: IDTechEx
Outside Reading

**Suzanne Berger, written testimony for the Senate Committee on Banking, Housing, and Urban Affairs Subcommittee on Economic Policy, December 2013**

In her testimony for a Senate subcommittee on economic policy, MIT political science professor Suzanne Berger explains how findings from the Institute’s sweeping study “Production in the Innovation Economy” show that manufacturing is the key to commercializing innovations in the United States. Berger highlights key survey results, including the finding that some of the most innovative firms in the U.S. are having trouble securing domestic funding to produce their products at scale, requiring them to seek financing abroad. More information related to the study appears in two books, *Making in America*, by Berger, and *Production in the Innovation Economy*, a compilation of related academic research.

**Erik Brynjolfsson, Andrew McAfee, and Michael Spence, “New World Order,” Foreign Affairs, July/August 2014**

This trio of academics argues that “advances in technology have created an increasingly unified global marketplace for labor and capital” and that the distinguishing characteristic of the most successful firms and national economies is rapidly becoming innovation. While the U.S. is recognized as an incubator of new ideas and entrepreneurs, they argue, that situation is not guaranteed to continue.


Breaking down earlier research on the component costs of an iPhone, the authors argue that it’s not China that’s cashing in on the manufacture of this American innovation but, rather, certain other developed nations, including Japan, South Korea, and Germany, which have become “masters of advanced manufacturing” and are making the phone components with the highest price tags.

**Conferences**

- **September 16–18, 2014**
  3D Printing & Additive Manufacturing Summit, Pittsburgh

- **September 21–24, 2014**
  Supply Chain Management Professionals Global Conference, San Antonio, TX

- **September 22–24, 2014**
  12th Global Conference on Sustainable Manufacturing, Johor Bahru, Malaysia

- **September 23–24, 2014**
  Advanced Manufacturing Expo Mississauga, Ontario

- **October 24–26, 2014**
  International Conference on Material Science and Engineering Technology, Beijing

- **November 11–13, 2014**
  Fabtech, Atlanta

- **November 14–20, 2014**
  ASME International Mechanical Engineering Congress & Expo, Montreal

- **December 8–10, 2014**
  American Supply Chain and Logistics Summit, Dallas

- **February 3–5, 2015**
  Expo Manufactura Mexico 2015, Monterrey

- **February 10–12, 2015**
  Pacific Design & Manufacturing, Anaheim, CA

- **March 23–26, 2015**
  Promat, Chicago

- **April 14–17, 2015**
  MTA Singapore, Singapore

- **April 19–23, 2015**
  Additive Manufacturing Users Group, Jacksonville, FL

- **April 20–23, 2015**
  AeroDef Manufacturing, Dallas

- **April 21–23, 2015**
  SAE 2015 World Congress & Exhibition, Detroit

- **June 8–12, 2015**
  International Manufacturing Research Conference, Charlotte, NC

- **June 24–27, 2015**
  Thailand’s Manufacturing Expo 2015, Bangkok

**PricewaterhouseCoopers, “3D Printing and the New Shape of Industrial Manufacturing,” June 2014**

Although there is substantial buzz around 3-D printing and what it can do, this survey of more than 100 manufacturers makes it clear that while many companies use the technology in some way, the majority are still figuring out what to do with it. Some 33 percent of the firms say they think it is “very unlikely” that 3-D printing will be used for high-volume production in the next three to five years. Even so, the authors predict that the market for 3-D printers will reach $6 billion by 2017, and they highlight some promising innovations in machines and materials that will open up more options for deploying the technology.
**MIT RESEARCH**

**Manufacturing-Related**

The following is a sample of MIT research in the areas of manufacturing, factories, fabrication, innovation and related topics.

A report on this same topic by MIT’s Industrial Liaison Program is available by request at the ILP website (Resources/Publications section) at http://ilp.mit.edu/webpub.jsp?brResearch=Y.

For a complete list of research reports by the MIT Industrial Liaison Program, please see the ILP website (Resources/Publications section) at http://ilp.mit.edu/webpub.jsp?brResearch=Y or contact the Industrial Liaison Officer for your company.

**Request ILP Research Report**

- Manufacturing-Related - 40 pages (PDF)

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**Programs / Initiatives**

**MIT Innovation Initiative**

[http://innovation.mit.edu/](http://innovation.mit.edu/)

The MIT Innovation Initiative is an Institute-wide, multi-year agenda to transform the Institute’s innovation ecosystem — internally, around the globe and with its partners — for accelerated impact well into the 21st century. The initiative builds upon MIT’s foundation of fundamental research excellence and supports the aspirations for impact through innovation of all members of the MIT community. It supports MIT’s focus on solving a range of critical challenges in energy, the health of the planet, human health and beyond.

The Initiative’s four primary areas of focus:

- Strengthening and expanding MIT’s innovation capabilities.
- Cultivating communities that connect us across MIT as well as engage us with broader worldwide innovation needs.
- Developing additional, transformative hands-on infrastructure.
- Formalizing, studying, and promoting the Science of Innovation.

**MIT.Nano**


MIT aims to harness the power of nanotechnology in service to humanity’s greatest challenges. MIT proposes to construct at the heart of the campus a new center for nanoscience and nanotechnology: an advanced facility open to the entire community of faculty, researchers, and students. A convening space to spark collaboration and cross-pollination. A hive for tinkering with atoms, one by one—and for constructing, from these fantastically small building blocks, a future of infinite possibility.

**BioManufacturing (BioMAN) Research Program**

[http://cbi.mit.edu/research-overview/bioman/](http://cbi.mit.edu/research-overview/bioman/)

The objective of the MIT Center for Biomedical Innovation (CBI) BioMANufacturing Research Program is to develop new knowledge, science, technologies and strategies that advance the manufacture and global delivery of high quality biopharmaceuticals. To address emerging biomanufacturing needs, BioMAN activities are focused on:

- Advanced product and process analysis for optimized quality manufacturing
- Flexible modular platforms for biotherapeutic production and delivery
- Assessment and mitigation of risk in biopharmaceutical production
- Global delivery of biopharmaceuticals
- Regulatory science

[http://cbi.mit.edu/research-overview/bioman/bioman-activities/](http://cbi.mit.edu/research-overview/bioman/bioman-activities/)

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**Manufacturing: Remaking the concept of making**

Viruses that self-assemble as parts of batteries. New methods to quickly mass-produce tailored nano-particles for medicine. Stronger, lighter airplanes constructed from carbon nanotube composites. Techniques to spin nanofibers a thousand times thinner than a human hair. Nanotechnology is not just producing new innovations—it’s enabling innovative ways to produce them.


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For a complete list of research reports by the MIT Industrial Liaison Program, please see the ILP website (Resources/Publications section) at http://ilp.mit.edu/webpub.jsp?brResearch=Y or contact the Industrial Liaison Officer for your company.
Laboratories, Centers, Groups

Computational Fabrication Group
http://cfg.mit.edu/

The Computational Fabrication Group at the MIT Computer Science and Artificial Intelligence Laboratory investigates problems in digital manufacturing and computer graphics... We have been developing a complete process and software/hardware framework that allows moving from abstract computer models to their physical counterparts efficiently and accurately. In the process, we have been addressing the following fundamental challenges: (1) developing representations and corresponding user-interfaces for designing complex, multi-material objects; (2) accurate and efficient simulation methods that can interactively predict properties and behavior of multi-material designs without physically generating it; (3) scalable and efficient architectures that convert multi-material models to inputs for 3D printers; (4) designing modular, high-resolution 3D printers that allow manufacturing multi-material composites made from a wide range of materials.

Mediated Matter Group
http://www.media.mit.edu/research/groups/mediated-matter

The Mediated Matter group is dedicated to the development and application of novel processes that enable and support the design of physical matter, and its adaptability to environmental conditions in the creation of form. Our research integrates computational form-finding strategies with biologically inspired fabrication. This enables mediating synergies between objects and environment; between humans and objects; and between humans and environment. Our goal is to enhance the relation between natural and man-made environments by achieving high degrees of design customization and versatility, environmental performance integration, and material efficiency. We seek to establish new forms of design and novel processes of material practice at the intersection of computer science, material engineering, design and ecology, with broad applications across multiple scales.

Interactive Robotics Group
http://interactive.mit.edu/

The Interactive Robotics group is a research lab at MIT developing innovative methods for enabling fluid human-robot collaboration. Our vision is to harness relative strengths of humans and robots to accomplish what neither can do alone. We focus on developing robots that work in teams with people in high-intensity and safety-critical applications, including industrial manufacturing, disaster response, and space exploration.

Projects

Building Innovative Capacity Among Massachusetts Manufacturers: Pathways and Opportunities for SMEs
Industrial Performance Center (IPC), http://ipc.mit.edu/research/production/building-innovative-capacity-smes

Building on its work in the Production in the Innovation Economy (PIE) initiative, the IPC has launched a new research project examining how small and medium-sized advanced manufacturing companies increase their innovative capacity.

Recent research by MIT’s Production in the Innovation Economy (PIE) commission highlighted two important points for today’s small and medium-sized advanced manufacturing companies. First, there is an important relationship between the U.S.’s ability to innovate and its manufacturing capabilities. Advanced manufacturing capabilities are essential for developing new products, processes and services across a range of industries. The loss of such capabilities can lead to the transition of industries to other countries as the innovation follows the manufacturing (as has been evident in a number of industries), and an inability to develop capabilities in new, emerging industries.

Second, the large, vertically-integrated corporations of the 1980s have deverticalized over time to focus on core competencies, outsourcing much of their production and often relying on smaller firms for their innovation. This process has left “holes” in the industrial ecosystem, with many of the important investments and spillovers that used to flow from the large corporations to smaller firms (e.g., in training, technology adoption, and R&D investments) no longer being made. The result is that many advanced small and medium-sized manufacturing enterprises (SMEs) have been left largely on their own to figure out how to find and train new workers, adopt new technologies, and develop and scale new products and services.

These findings underscore both the importance of advanced manufacturing SMEs to the country’s ability to innovate and grow, and the need for a more intentional and systematic approach toward developing SME capabilities to the needs of the larger original equipment manufacturers (OEMs) that are typically their customers.

This is especially important in a state such as Massachusetts, given the diversity and sophistication of the industries in which the over 7,500 advanced manufacturers in the state are engaged (e.g.,
agglomerations. Over a two-week period, this study set out to understand the discrete activities underpinning the economic dynamics of an industrial agglomeration. Over a two-week period, data was collected by employing the geolocative capabilities of Foursquare, a social media application, to record every movement of fashion workers employed at fashion design firms located both inside and outside the geographical boundaries of New York City's Garment District. This unique method of studying worker activity exposed the day-to-day dynamics of an industrial district with a precision thus far undocumented in literature. Our work suggests that having access to the cluster provides almost the same agglomeration economies as residing within its borders.

http://dusp.mit.edu/project/industry-motion

As many of you know, the Garment District has been under enormous pressure to rezone over the past several years. This proposal could possibly erode the way in which designers are able to work and innovate. During summer of 2011, the Spatial Information Design Lab, in partnership with Elizabeth Currid, set out to quantify the importance of manufacturing firms in the Garment District. In this project we used smart phone technology to perform a survey of the spatial patterns of New York City design firms. We believe that their spatial patterns will show that the density of manufacturing in the garment district matters to the industry.

In order to survey the spatial patterns of the fashion industry workforce we will ask participants in the study to use anonymously generated FourSquare accounts to "check-in" to fashion related locations. These "check-ins" will allow us to see how and where fashion industry workers use the Garment District. We believe the findings will show that proximity matters to New York City's fashion industry.

http://www.checkinfashion.com/
http://www.civicdatadesignlab.org/#/new-gallery/

Industry in Motion
Prof. Sarah Williams, Civic Design Data Lab
http://dusp.mit.edu/faculty/sarah-williams ;
http://www.civicdatadesignlab.org/

Industrial agglomerations have long been thought to offer economic and social benefits to firms and people that are only captured by location within their specified geographies. Using the case study of New York City's garment industry along with data acquired from cell phones and social media, this study set out to understand the discrete activities underpinning the economic dynamics of an industrial agglomeration.

http://www.civicdatadesignlab.org/#/new-gallery/

Risks and Scalability of New Technologies
Prof. Jessika Trancik, Atlantic Richfield Career Development Assistant Professor in Energy Studies
http://trancik.scripts.mit.edu/home/

We are developing methods to assess the risks of existing and new technologies in terms of cost and other performance metrics, and how these risks might change in interesting and important ways with the scale of adoption.

Many evaluations of technologies focus on their long-term potential for improvements due to innovation, but the short-term riskiness of technologies is also important for evaluating their viability. Short-term risks can arise, for example, from changes in efficiency and cost. Moreover, the overall riskiness of technologies can change with production scale. Here we analyze data and develop models to assess technologies based on their riskiness...

...Evaluating the scalability of PV input materials: Photovoltaics (PV) is an energy technology that is promising in its climate change mitigation potential. In order to sustain rapid growth in PV manufacturing, it is important to produce a sufficient quantity of input materials in a cost-effective and timely manner. In this project we evaluate the material requirements of large-scale PV deployment and the supply risks associated with these materials.

In the first part of this project, we ask whether metals production can be scaled up at a pace that matches the rapidly increasing PV deployment levels put forward in aggressive low-carbon energy scenarios. We present a new perspective on the metal requirements of PV deployment by estimating the growth rates required for the annual production of PV metals to satisfy the projected PV deployment levels in 2030. We also compare the required growth rates to the historical growth of a large set of metals in order to assess how realistic the projections are.

ADDITIVE MANUFACTURING: FROM 3D PRINTING TO THE FACTORY FLOOR
July 27-31, 2015, Tuition $4,500, MIT Campus, Prof. John Hart
http://web.mit.edu/professional/short-programs/courses/additive_manufacturing.html

This course will build a comprehensive understanding of additive manufacturing (AM) processes and their implications for product development and manufacturing operations. Lectures will analyze AM fundamentals, materials, and process capabilities. This content will then be related to applications spanning industries including aerospace, medical devices, electronics, architecture, and consumer products. Lab sessions will provide hands-on experience with desktop 3D printers. Participants will design, fabricate, and measure components, and will identify future opportunities via case studies.

FLOW CHEMISTRY: CONTINUOUS SYNTHESIS AND PURIFICATION OF PHARMACEUTICALS AND FINE CHEMICALS
July 13-15, 2015, Tuition $2,850, MIT Campus, Prof. Joel Schindall, Blade Kotelly
http://web.mit.edu/professional/short-programs/courses/mastering_innovation_and_design_thinking.html

Learn to think like a designer to create phenomenal products and services. Using a 10-step design process and a 3-step vision-creation process, this highly interactive class will expand your thinking and develop techniques to help you and your organizational teams create more powerful and successful solutions.

RADICAL INNOVATION
June 8-10, 2015, Tuition $2,600, MIT Campus, Prof. Sanjay Sarma
http://web.mit.edu/professional/short-programs/courses/radical_innovation.html

The course will cover a range of topics in innovation. We will start by understanding what makes a successful innovative product and business: People, Opportunity, Context, and Technology. We will examine case studies in what we call radical innovation and will identify steps that companies can take towards encouraging innovations from within, ranging from brainstorming sessions to invention awards. We will also examine successful incubator strategies and critical success factors and some of the IP issues around invention. Next, we will explore the role of venture funds inside and outside companies, and discuss spinouts, spin-ins, licensing, and acquisitions.

Finally, we will consider the role of communities, standards bodies, and open-source models in innovation. We will have breakout sessions in which smaller groups will engage in innovation exercises.

RAPID PROTOTYPING TECHNOLOGY (NEW COURSE)
July 20-24, 2015, Tuition $5,000, MIT Campus, Prof. Martin Culpepper
http://web.mit.edu/professional/short-programs/courses_topic.html#dam

Participants will obtain hands-on exposure to processes commonly used to rapidly fabricate prototypes. Classroom time covers an introductory-level review of the principles that govern the technologies, design for manufacturing, and best practices. Laboratory time includes design of representative components, observation of fabrication by MIT staff, and measurement/inspection of the resulting parts. The course materials cover 3D printing, Laser Cutting (polymers), Waterjet Cutting (metals and polymers), CNC milling (metals and polymers), CNC turning (metals and polymers), thermoforming (polymers), silicone molding, and a CNC router (wood and/or foam).