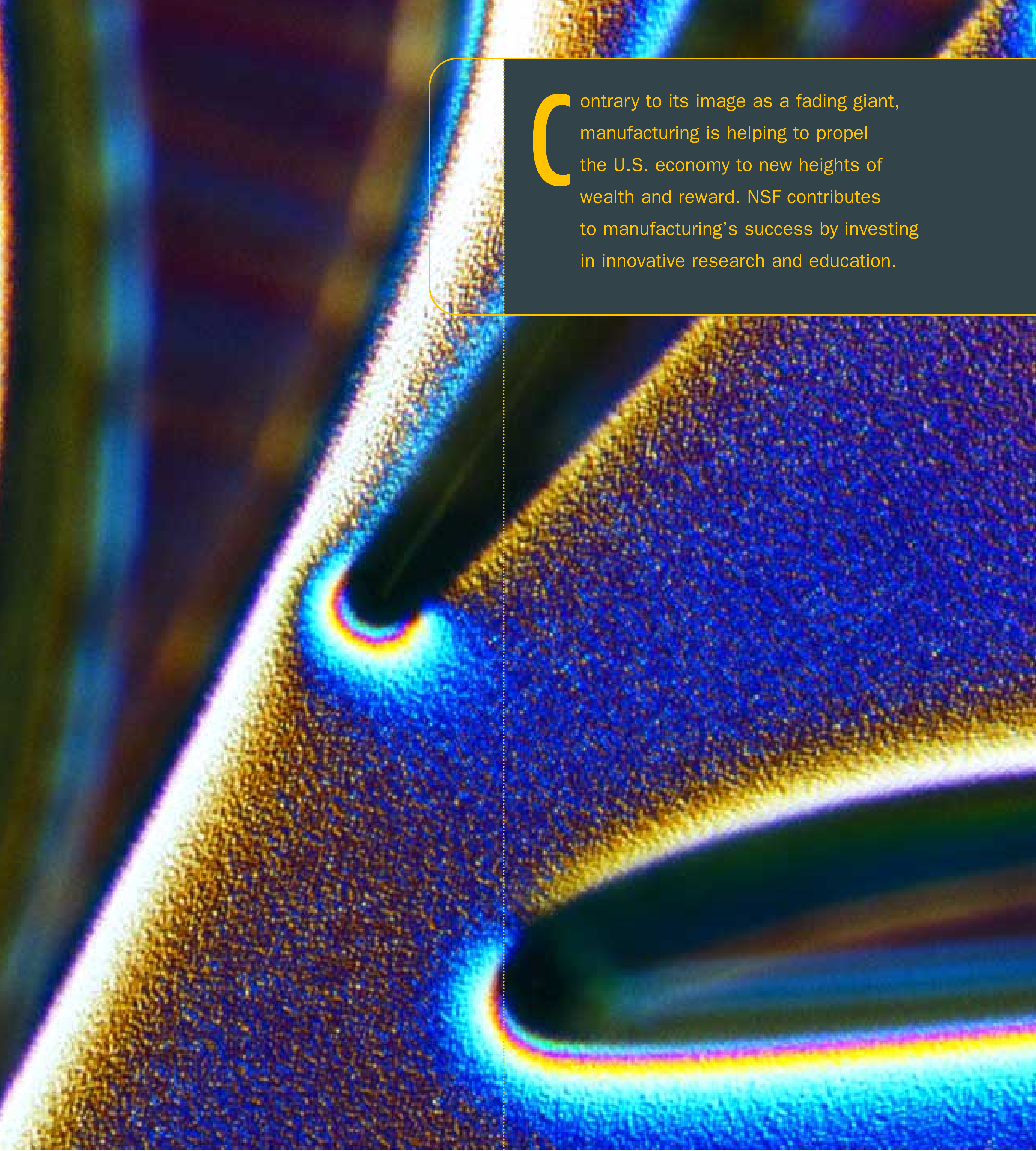
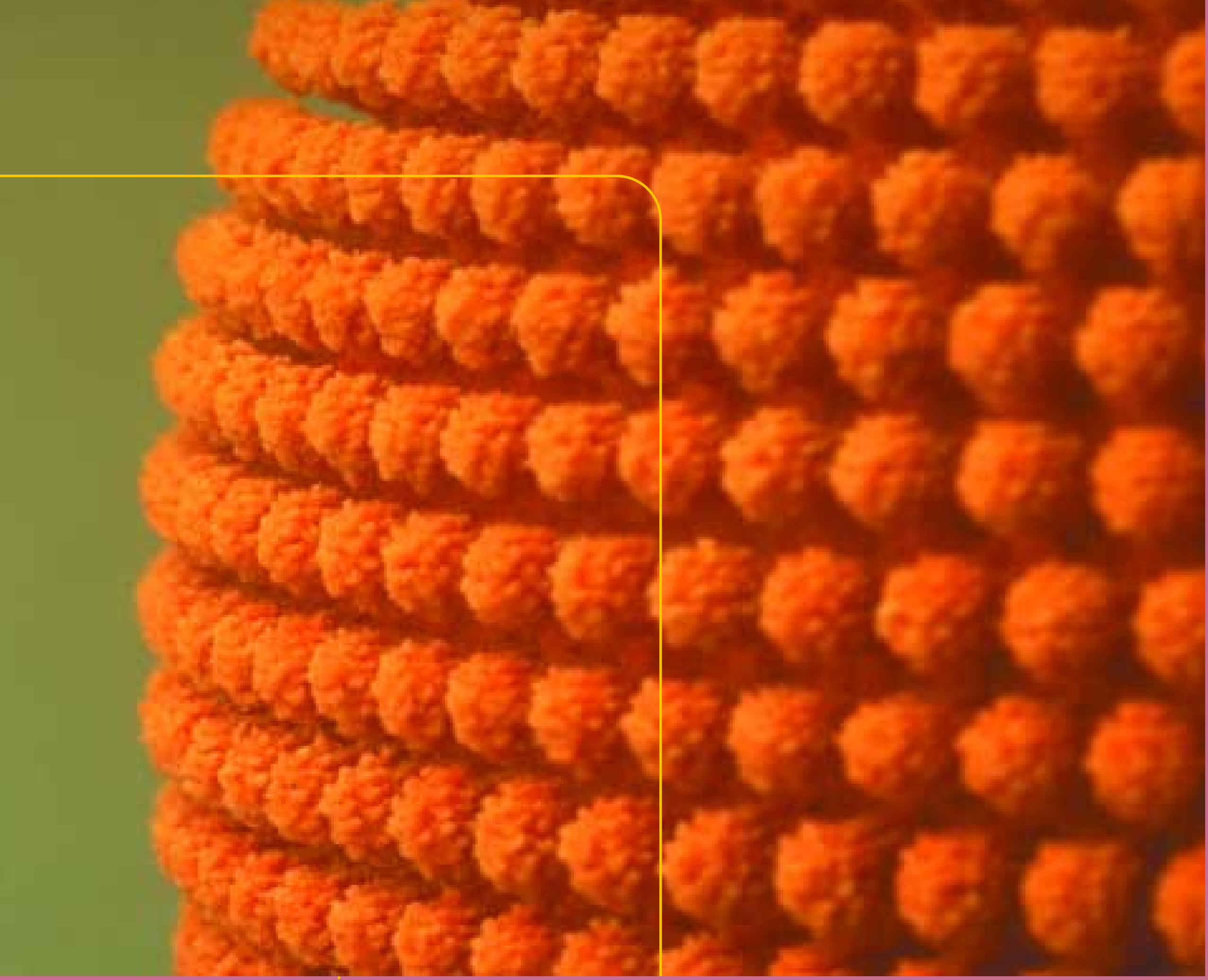
Manufacturing

the form of things unknown



Contrary to its image as a fading giant, manufacturing is helping to propel the U.S. economy to new heights of wealth and reward. NSF contributes to manufacturing's success by investing in innovative research and education.



Manufacturing**—the process of converting dreams into objects that enrich lives—is the poetry of the material. Traditionally, the path from an engineer's imagination to a finished prototype was labyrinthine, involving draftsmen, model makers, rooms full of machine tools, and lots of time. But all that is changing. Over the last two decades, NSF grants have helped to create new processes and systems as well as innovative educational programs that have transformed manufacturing from a venture dominated by smoke-belching factories to the clean and agile enterprises of today and tomorrow.**

The Myth of Manufacturing's Demise

Here at the close of the twentieth century, manufacturing accounts for one-fifth of the nation's gross domestic product and employs 17 percent of the U. S. workforce, according to the National Science and Technology Council. More significantly to the nation's economic well-being throughout the 1990s, productivity in manufacturing—the ability to produce more goods using less labor—far outstripped productivity in all other sectors of society, including the service sector. As the nation's productivity leader, manufacturing has helped the nation to achieve low unemployment with only modest inflation.

"Other sectors generate the economy's employment," says National Association of Manufacturers economist Gordon Richards. "Manufacturing generates its productivity."

This record of success seems remarkable when compared to the state of manufacturing just twenty-five years ago.

"There was a lot of literature in the mid-seventies that argued quite strongly that the United States was basically going to a service economy," says Louis Martin-Vega, NSF's acting assistant director for Engineering and former director of the Directorate's Division of Design, Manufacture, and Industrial Innovation (DMII). Back then, Americans worried while clean, efficient Japanese factories rolled out streams of products—cars, televisions, VCRs—that were of higher quality and lower cost than those produced in the United States.

Still based on the classical mass-production model pioneered by early automaker Henry Ford, American manufacturing was proving no match for the leaner, more flexible manufacturing techniques that, although first conceived by American thinkers, were being improved upon elsewhere. In order to modernize manufacturing processes and systems, however, U.S. businesses needed to do the kind of research and development (R&D) that was becoming too expensive for any one business to undertake by itself. Government help was required, but in the early 1980s, help was hard to come by: The push was on to beef up defense and shrink the rest of the federal government, all while rampant inflation eroded existing research budgets. The result at NSF, according to Dian Olson Belanger, author of *Enabling American Innovation: Engineering and the National Science Foundation,* was that "in real purchasing power, 1982 [research] grantees were living with dollars adequate for 1974."

By the mid-1980s, the United States was no longer "the unquestioned technological hub of the world," according to Harvard physicist and Nobel Laureate Sheldon Glashow, but was instead passing "the torch of scientific endeavor" to other nations. "Steel, ships, sewing machines, stereos, and shoes" were "lost industries," he said. Unless something was done soon, Glashow exclaimed, Americans would be left with "their Big Macs . . . and perhaps, [their] federally subsidized weapons industries."

The NSF-supported Integrated Manufacturing Systems Laboratory (IMSL) at the University of Michigan is developing next-generation manufacturing systems that can be quickly reconfigured to adapt to changing market realities. Research focuses on open architecture controls, reconfigurable machining systems, and sensor-based monitoring systems. Here, graduate students demonstrate their work in the lab during a visit by NSF officials.

Says Martin-Vega of that troubling time, "There was a realization that, well, we've lost the electronics business, the automotive industry was hurting, the machine-tool industry was all Germany and Japan, and then it seemed like we were going to have the same fate in the semiconductor industry."

The potential loss of an industry so crucial in the burgeoning Computer Age frightened public officials and turned federal attention to manufacturing-related research in a new way. In 1987, the government worked with industry to start a research consortium of semiconductor companies known as SEMATECH. The group continues to operate today (having weaned itself from government support) with member companies sharing expenses and risk in key areas of semiconductor technology research.

Within NSF, says Martin-Vega, "The argument for supporting work in manufacturing was made less difficult when you had a situation that could almost be considered a national threat." Engineering research seeds planted in the early 1970s began to bear fruit. By the mid-1980s, some pivotal scientific foundations for design and manufacturing were in place. To build on them, in 1985 NSF established a separate design and manufacturing division.

NSF helped to move manufacturing from the obituaries to the headlines, which now are more likely to celebrate the "new manufacturing," with its reliance on information technologies and more malleable, quick-response organizational structures. As the following highlights demonstrate, with some critical assistance from NSF, U.S. manufacturing isn't dying after all—it's just changing.

Rapid Prototyping

In the late 1960s, Herbert Voelcker—then an engineering professor at the University of Rochester, now at Cornell University—went on sabbatical and asked himself how to do "interesting things" with the automatic, computer-controlled machine tools that were just beginning to appear on factory floors. In particular, Voelcker wanted to find a way to take the output from a computer design program and use it to program the automatic machine tools.

With funding from NSF, Voelcker tackled the problem first by developing the basic mathematical tools needed to unambiguously describe three-dimensional parts (see the chapter on "Visualization," p. 88). The result was the early mathematical theory and algorithms of solid modeling that today form the basis of computer programs used to design almost everything mechanical, from toy cars to skyscrapers.

During the 1970s, Voelcker's work transformed the way products were designed, but for the most part they were still made the same old way. That is, either a machinist or a computer-controlled machine tool would cut away at a hunk of metal until what remained was the required part, in much the same way as Michelangelo removed chips of marble from a block until all that remained was a statue of David. But then in 1987, University of Texas researcher Carl Deckard came up with a better idea.

Next-Generation Manufacturing

Since 1976, various U. S. presidents have formed interagency councils—with gradually increasing participation from industry—to try to build consensus and identify strategies in certain key areas of the economy, including manufacturing. NSF's leadership has been critical to these efforts, which most recently took the form of the Next-Generation Manufacturing (NGM) project.

NGM was funded by NSF and other federal agencies but headed by a coordinating council drawn from the manufacturing industries. Starting in 1995, more than 500 industry experts worked together to produce a final 1997 report offering a detailed vision for the future of manufacturing. Today the NGM report forms the basis of a follow-up effort called the Integrated Manufacturing Technology Roadmap (IMTR) project, also funded by NSF and other federal agencies.

"The question that guided us," says NSF's Deputy Director Joseph Bordogna, former head of NSF's Directorate for Engineering and a primary architect of NGM and other efforts to rejuvenate manufacturing in America, "is 'what principles underlie the ability of a company to continuously change itself in response to the changing marketplace?' That means figuring out adaptive, decision-making processes and software, as well as manipulating materials and coming up with new machines for the factory floor."

According to the NGM report, a "next-generation" manufacturer will need to transform itself from a twentieth century-style company—one that functions as a sovereign, profit-making entity—into a twenty-first century company that is more of an extended enterprise with multiple and ever-shifting business partners. As Stephen R. Rosenthal, director of the Center for Enterprise Leadership, describes it, next-generation manufacturers should be companies that stretch from "the supplier's supplier to the customer's customer."

Successful next-generation manufacturers, the NGM report concludes, will have to possess an integrated set of attributes. The company will need to respond quickly to customer needs by rapidly producing customized, inexpensive, and high-quality products. This will require factories that can be quickly reconfigured to adapt to changing production and that can be operated by highly motivated and skilled knowledge workers. Workers organized into teams—both within and outside a company—will become a vital aspect of manufacturing. As participants in extended enterprises, next-generation companies will only undertake that part of the manufacturing process that they can do better than others, something industry calls "adding value."

Inherent in these requirements are what the NGM project report calls "dilemmas." These arise from the conflict between the individual company's needs and those of the extended enterprise. How can knowledge be shared if knowledge is itself a basis for competition? What security can companies offer their skilled employees when the rapidly changing nature of new manufacturing means that firms can't guarantee lifetime employment? How can the gaining of new knowledge be rewarded in a reward-for-doing environment?

Resolving these dilemmas is an important part of NSF's vision of the work to be done in the twenty-first century, work in which NSF will play a leading role.

NSF helped launch rapid prototyping technologies, which can build new products from a computer-aided design (CAD) model without any carving or machining. Here, a student works with rapid prototyping equipment in the NSF-supported Advanced Design and Manufacturing Laboratory at the University of Maryland. One goal of the lab is to create graphical materials for visually impaired students.

Instead of making a part by cutting away at a larger chunk of material, why not build it up layer by layer? Deckard imagined "printing" three-dimensional models by using laser light to fuse metallic powder into solid prototypes, one layer at a time.

Deckard took his idea—considered too speculative by industry—to NSF, which awarded him a $50,000 Small Grant for Exploratory Research (SGER) to pursue what he called "selective laser sintering." Deckard's initial results were promising and in the late 1980s his team was awarded one of NSF's first Strategic Manufacturing (STRATMAN) Initiative grants, given to the kind of interdisciplinary groups often necessary for innovation in the realm of manufacturing.

The result of Voelcker's and Deckard's efforts has been an important new industry called "free form fabrication" or "rapid prototyping" that has revolutionized how products are designed and manufactured.

An engineer sits down at a computer and sketches her ideas on screen with a computer-aided design program that allows her to make changes almost as easily as a writer can change a paragraph. When it's done, the design can then be "printed" on command, almost as easily as a writer can print a draft—except this draft is a precise, three-dimensional object made of metal or plastic.

"To take a computer model and turn it into a physical model without any carving or machining is incredible," says an analyst who tracks this new industry. "It's almost like magic when you see that part appear."

The method can be used to make things that are more than prototypes. "Because you can control it in this incredible way, you can make objects that you just couldn't think of machining before," says George Hazelrigg, group leader of DMII's research programs. "For example, you can make a ship in a bottle."

More practically, the method has been used to make a surface with lots of tiny hooks that resembles Velcro. These new surfaces are proving to be ideal substrates for growing human tissue. NSF-funded researchers have already grown human skin on these substrates and are looking to grow replacements of other organs as well.

"So these are pretty fundamental things," Hazelrigg says. "I think it's fair to say that we played a major role in it."

Bruce Kramer, acting division director of NSF's Engineering and Education Centers, is even more definite: "For a majority of successful rapid prototyping technologies, the first dollar into the technology was an NSF dollar."

Getting Control

Rapid prototyping may be the wave of the future but most manufacturing is still done by traditional machine tools—the drills, lathes, mills, and other devices used to carve metal into useful shapes. Machine tools have been around for more than two centuries, only recently changing to keep time with the revolution in computer technology. Through most of the 1980s, computer-controlled machine tools were capable of only a narrow range of preprogrammed tasks, such as drilling holes or cutting metal according to a few basic patterns. For simple designs these controllers were pretty good, but by 1986, when University of California engineering professor Paul Wright applied to NSF for a grant to improve machine tools, the limitations of these so-called closed architecture controllers were becoming apparent.

"Our goal was to build a machine tool that could do two things," Wright explains. "Number one, be more connected to computer-aided design images so that if you did some fantastic graphics you could actually make the thing later on. Number two, once you started making things on the machine tool, you wanted to be able to measure them *in situ* with little probes and then maybe change the machine tool paths" to correct any errors.

The idea was to devise a controller that was flexible both in hardware and software, allowing the use of advanced monitoring and control techniques based on the use of sensors. Wright also wanted to standardize the basic system so others could more easily develop new hardware and software options over time.

At first, Wright asked machine tool manufacturers to support his research, but "they thought I was a complete idiot," he recalls. Wright wanted to use the relatively new Unix operating system, which the machine tool companies thought was daring and unsafe. So Wright and his colleagues turned to NSF. The agency responded, says Wright, with a grant "to open up the machine tool controller box, which was very crude and inaccessible back then. And, in my humble opinion, that has led to a lot of good results."

Today, Wright's open architecture controllers are the industry norm and have quite literally changed the shape of manufactured products. That NSF was there when even the ultimate beneficiary—industry—was not, is "why I'm so enthusiastic about NSF," Wright says.

Supply Chain Management

Rapid prototyping and open architecture controllers are examples of advances in manufacturing processes, but NSF has also been instrumental in helping to modernize manufacturing systems.

In 1927, Henry Ford's Rouge complex near Detroit began churning out a ceaseless stream of Model A cars. The Rouge facility was perhaps the ultimate expression of mass production and "vertical integration," in which a company tries to cushion itself from the vagaries of the market by owning or controlling virtually every aspect of its business, from the mines that provide the ore to the factories that make the glass. Raw materials—iron ore, coal, and rubber, all from Ford-owned mines and plantations—came in through one set of gates at the plant while finished cars rolled out the other.

Ford's vision informed how manufacturing was done for most of the twentieth century, but by the late 1970s the limitations of this approach had started to become obvious, at least to the Japanese. Why make steel if what you do best is make cars? Why be responsible for your own suppliers—and pay to maintain all that inventory—when it's cheaper to buy from someone else? Bloated, vertically integrated American companies faced a serious challenge from Japanese carmakers who organized their factories along a different, leaner model resulting in cheaper, better cars. Japanese factories—in which each car was built by a small team of workers rather than being pieced together along a rigidly formulated assembly line—were far more efficient when it came time to shift to a new model. An American car plant was like a machine dedicated to building a single type of vehicle. Workers were interchangeable parts of that machine, whose "intelligence" was vested in the machine's overall design rather than in the workforce. In contrast, Japanese plants depended on the intelligence of their workers, who were encouraged to make any improvements to the manufacturing process that they saw fit.

It took some time, but by the 1980s American manufacturers such as General Motors (GM) had absorbed the Japanese lessons of “lean” manufacturing and were looking to make some improvements of their own. For help, GM turned to Wharton Business School professor Morris Cohen who, with support from NSF, analyzed a critical part of its production system: The process by which GM distributed 600,000 repair parts to more than a thousand dealers.

Cohen’s approach was to see this process as one of many “supply chains” that kept GM up and running. Supply chains form a network of resources, raw materials, components, and finished products that flow in and out of a factory. Using empirical data and mathematical models, Cohen and his colleagues proposed a complete reorganization of GM’s repair parts supply chain.

“We suggested that a high degree of coordination be put in place to connect decisions across the supply chain,” says Cohen. “Today that’s commonplace, but back then the idea was considered radical.”

In fact, the idea was considered so sweeping that GM executives rejected it—not because they disagreed with Cohen’s analysis but rather because the scale of the reorganization was too much for them to contemplate at the time. However, GM was soon to embark on building a new car company called the Saturn. GM’s management decided to apply a number of Cohen’s recommendations to the new venture, including the main proposition: centralized communications and coordinated planning among the Saturn dealerships and the company distribution center. Rather than operating in the traditional fashion, as separate entities, the dealerships would be hooked up via satellite to a central computer. By consolidating information and making it available to everyone, management could make optimal parts-ordering decisions, neighboring dealerships could pool resources, and dealers could focus on maximizing customer service without worrying about what inventory they should be stocking. All of these improvements let management accommodate difficult-to-predict parts service demands without holding excessive inventory, while still ensuring that dealers got the parts they needed to repair cars in a timely manner.

Cohen’s approach to supply chain management quickly proved a success: Saturns, which are relatively low-cost cars, are routinely ranked among the top ten cars with respect to service. “The other top ten are high-priced imports,” Cohen says.

Only the Agile Survive

Supply chain management may make for leaner manufacturing, but there is also a premium on agility. Agile manufacturers recognize that information technology and globalization have dramatically quickened the rate at which new products must be innovated and brought to market. In such a rapidly shifting marketplace, it’s best to operate not as a vertically integrated giant but rather as part of a loose confederation of affiliates that form and reform relationships depending on changing customer needs. In the 1990s, NSF set up three institutes—at the University of Illinois, Rensselaer Polytechnic Institute (RPI), and the University of Texas at Arlington—to study issues raised by agile manufacturing.

A Brief History

Manufacturing, because it is a multi-faceted endeavor depending on the integration of many ideas, techniques, and processes, draws largely on the skills of engineers, a group that has not always felt entirely welcome at NSF. Vannevar Bush, head of the wartime Office of Scientific Research and Development, wrote a major report for President Harry Truman that led to the establishment of NSF in 1950. In that report, Bush warned that while America was already preeminent in applied research and technology, “with respect to pure science—the discovery of fundamental new knowledge and basic scientific principles—America has occupied a secondary place.”

As a result of this view many came to see engineering, rightly or wrongly, as a quasi-applied science that, says historian Dian Olson Belanger, “was always alien to some degree” within the historically basic science culture of NSF.

This attitude began to change during the post-Sputnik years and continuing through the Apollo moon landing, when engineering gradually assumed a more prominent role at NSF. President Lyndon Johnson amended the NSF charter in 1968 specifically to expand the agency’s mission to include problems directly affecting society. Now “relevance” became the new by-word, embodied in the 1969 launch of a new, engineering-dominant program called Interdisciplinary Research Relevant to Problems of Our Society (IRRPOS), which funded projects mostly in the areas of the environment, urban problems, and energy.

IRRPOS gave way in 1971 to a similar but much expanded program called Research Applied to National Needs (RANN). And within RANN, an NSF program officer named Bernard Chern began to fund pioneering research in computer-based modeling, design, and manufacturing and assembly processes.

“It is fair to say that Chern’s early grantees . . . set the character of much of American automation and modeling research for almost a decade,” says Herbert Voelcker, former deputy director of DMII and now an engineering professor at Cornell University. But despite its successes, RANN remained controversial among those concerned that NSF not lose sight of the importance of curiosity-driven research. Still, by the time RANN was abolished in 1977, it had built a substantial beachhead within NSF for problem-oriented and integrative R&D.

In 1981, NSF was reorganized to establish a separate Directorate for Engineering. As part of its mandate to invest in research fundamental to the engineering process, the directorate includes specific programs devoted to design and manufacturing issues. Today such issues are the province of the Division of Design, Manufacture, and Industrial Innovation, whose mission is to develop a science base for design and manufacturing, help make the country’s manufacturing base more competitive, and facilitate research and education with systems relevance.

NSF-funded researchers at the University of California at Berkeley, have created an experimental system called CyberCut that allows users to quickly design and manufacture prototypes for mechanical parts via the Internet. An online computer modeling tool links to a computer-controlled milling machine. Here, Cybercut renders art—a human face scanned by lasers.

"Agile manufacturing takes on a slightly different definition depending on whom you talk to," says Robert Graves, who is a professor in the Decision Sciences and Engineering Systems department at RPI as well as director of the Electronics Agile Manufacturing Research Institute, which studies issues of agile manufacturing as they apply to the electronics industry. "Here in electronics we look at the idea of distributed manufacturing."

In the distributed manufacturing model, an enterprise consists of a core equipment manufacturer that produces the product and is supported by supply chains of materials manufacturers and services. As an exercise, Graves and his colleagues at RPI set up their own agile "company" to redesign a circuit board used in an Army walkie-talkie. While team members finished the product's design, companies were found that could potentially supply the parts and assembly services required. But parts listed in the companies' catalogs weren't always available or, if they were, might not have been available quickly.

So the team redesigned their circuit board to include other, more readily available parts. This, and the search for new suppliers, took excessive time and required extra resources—circumstances that emulated the realities of traditional design and manufacturing. But the time wasn't wasted, since the whole point was to identify common manufacturing obstacles and devise ways for the system to become more agile.

In the end, the RPI researchers saw that they could streamline the system by using computers and networks to handle the negotiations between suppliers and designers. The researchers developed software that takes a circuit board design, works out all possible, functionally equivalent variants, and sends out "agents"—self-sufficient computer programs—to the computers of the various parts suppliers. These automated agents carry a "shopping" list of the physical characteristics of some sub-system of the board. List in hand, each automated agent essentially roots around in the suppliers' computers, making note of such things as how much each supplier would charge for the components on the list and how quickly the supplier can deliver. The agents then carry the information about pricing and availability back to the designer's computer, which may use the new data to further modify the design and send out yet more agents.

RPI researchers using this new system cut the circuit board design process from a typical nine months to a matter of weeks. In 1999, the group spun off a company called ve-design.com to market their newly developed agile system.

Education that Works

The success of supply chain management and agile manufacturing shows that manufacturing cannot be considered primarily in terms of transforming raw materials into finished goods, says Eugene Wong, former director of NSF's Directorate for Engineering and currently professor emeritus at the University of California at Berkeley. Rather, manufacturing should be thought of as a "system function" that serves as the core of a modern production enterprise.

"In a larger sense," says Wong, "the distinction between manufacturing and service is not useful. Modern manufacturing encompasses inventory management, logistics, and distribution—activities that are inherently service-oriented." Wong suggests that this blurring of the manufacturing and service sectors of the economy constitutes a paradigm shift with profound implications for the future. That is why NSF continues to invest not only in the development of new manufacturing processes and systems, but also in new approaches to engineering education. As NSF Deputy Director Joseph Bordogna says, "It's not just the discovery of new knowledge, but the education of workers in that new knowledge that is the fundamental—and maybe unique—mission of NSF."

The education of both scientists and engineers has been a goal of NSF since 1950. During the economic turbulence of the 1970s and 1980s, however, it became clear that industry and academia had become estranged from each other in the critical area of manufacturing. Manufacturing-related scientific research at the universities wasn't making it out into the real world quickly enough, if at all, and companies were complaining that their young engineering hires, while capable of scientifically analyzing a problem, couldn't produce actual solutions in a timely fashion. So NSF began looking for ways to nurture mutually beneficial partnerships between companies seeking access to cutting-edge research and students and professors looking for practical experience in putting their ideas to work.

In the early 1980s, NSF spearheaded what was then known as the Engineering Faculty Internship Program. The program provided seed grants—to be matched by industry—for faculty members interested in spending time in an industrial environment. A decade later, the internship model was included as part of a broader program aimed at creating opportunities for universities and industries to collaborate on long-term, fundamental research. Eventually the expanded program, called Grant Opportunities for Academic Liaison with Industry (GOALI), spread throughout the whole of NSF.

Research funded through the GOALI program has led to such advances as more efficient chip processing and improvements in hydrocarbon processing, which allow previously unusable heavy oils to be transformed into gasoline and chemical products.

"GOALI enhances research," says NSF's GOALI coordinator, Mihail C. Roco. "The program has unlocked a real resource in academic and industrial research. GOALI promotes basic research that can provide enormous economic benefits for the country."

Another effort by NSF to bridge the gap between industry and academia is the Engineering Research Centers (ERC) program, launched in 1984. The ERC program supports university-based research centers where industry scientists can collaborate with faculty and students on the kind of knotty, systems-level engineering problems that tend to hobble innovation in the long run. Companies get a chance to conduct cutting-edge research with a long-term focus while faculty and students (both graduate and undergraduate) become more market-savvy in their approach to problem-solving. In the end,

A student at the NSF-supported Microelectronics Lab at the University of Arizona adjusts the water flow to an apparatus used to study wafer rinsing, a critical step in the manufacture of semiconductor chips. Current methods use huge amounts of water, an environmental concern. Through the fundamental study of wafer rinsing, NSF-funded researchers have discovered bottlenecks in the process and have created optimal flow cycles to reduce waste.

ERCs shorten the path between technical discovery and the discovery's application.

"The basic goal of the ERC program is to form partnerships within industry to advance next-generation technology and to develop a cadre of students who are much more effective in practice," explains NSF's Lynn Preston, ERC program leader. "Because of the sustained support that we can give them, the centers focus and function with a strategic plan."

ERCs focus on relatively risky, long-term research—the kind that industry, coping with an increasingly competitive marketplace, is often reluctant to chance. "It's about really big, tough challenges that industries can't take on their own," says Preston.

A prime example with regard to manufacturing is the Center for Reconfigurable Machining Systems (RMS) at the University of Michigan in Ann Arbor. Since its establishment as an ERC in 1996, the RMS center has aimed to create a new generation of manufacturing systems that can be quickly designed and reconfigured in response to shifting market realities. Working with about twenty-five industry partners, the students and faculty of the RMS center seek to develop manufacturing systems and machines with changeable structures.

"Most manufacturing systems today have a rigid structure," says Yoram Koren, the RMS center's director. "Neither the machines themselves or the systems they're a part of can be changed very easily. But with the globalization of trade, product demand is no longer fixed and product changeover becomes faster. Companies need to be able to adjust their product lines, often incrementally, to changing market realities."

Koren points to the automotive industry as an example. "When gas prices were low, everybody wanted to buy a V-8 [engine]," he says. "Car companies couldn't make enough V-8 engines to supply demand. Now gas prices are going up and companies are facing the opposite problem."

One common barrier to change is what's known as "ramp-up." Usually, it takes anywhere from several months to three years to ramp up; that is, to begin marketing an optimum volume of flaw-free new products once a new manufacturing system is put into place. A key contributor to the delay is the inherent difficulty in calibrating changes throughout the existing system; a single machine error can propagate and cause serious product quality problems. To address this issue, the students, faculty, and staff at the RMS center have come up with a mathematically based "stream-of-variation" method that Koren says significantly reduces ramp-up time. The center's industry partners are excited about the prospects for this and other RMS-generated innovations.

"We, and our suppliers, have already benefited from working with University of Michigan researchers to implement scientific methods in our plants," says Jim Duffy, manager of manufacturing engineering at Chrysler Corporation.

Mark Tomlinson, vice president for engineering at Lamb Technicon (a major machine tool builder), agrees about the potential pay-off for industry. "The ERC for Reconfigurable Machining Systems is providing the vision and inspiration for our next-generation machines," he says, "as well as supplying the qualified engineers that support our needs."

Manufacturing the Future

The ERC program is a particularly good example of how NSF brings together the discovery-driven culture of science and the innovation-driven culture of engineering. Manufacturers applaud NSF's efforts because they recognize that coming up with new systems and products is a much more complex and expensive venture than ever before, and they need the help of university-based researchers in order to build the science base for future advancements.

For example, it takes about a billion dollars to develop a new semiconductor chip capable of the kind of performance required in, say, high-definition television. That level of investment—that level of risk—deters even the most ambitious American companies from doing the kind of pioneering research necessary to keep them globally competitive. NSF's role as a catalyst for government-industry-academia collaboration is vital for the nation's economic well-being.

"You need a partnership," says NSF Deputy Director Joseph Bordogna. "You need new knowledge out of universities and labs, new processes from industry, and a government willing to enable it all through appropriate R&D policy and frontier research and education investment, by and for the citizenry."

NSF's efforts to bridge the worlds of industry and academe reflect another truth about modern manufacturing: Knowledge and ideas are the most important raw materials.

"It's no longer profitable just to ship a piece of metal out the front door," industry analyst Graham Vickery told *Industry Week*. "What you're doing now is shipping some sort of component that requires things like support services, or advice, or design skills, or engineering know-how" in order for the component to be of actual use at the other end.

Finding innovative ways to handle information is now manufacturing's chief concern. "If you understand that today manufacturing is an enterprise-wide production process," says Eugene Wong, "you see that information management will assume an increasingly important role, one that may already have transcended the importance of transforming materials into products."

With NSF's help, American manufacturers are making the changes necessary to stay competitive in a marketplace increasingly dominated by e-commerce, while at the same time honoring the traditional core of manufacturing's purpose: the innovation of new technologies and products for an expectant public.

To Learn More

NSF Directorate for Engineering
www.eng.nsf.gov

NSF Division of Design, Manufacture, and Industrial Innovation
www.eng.nsf.gov/dmii

Engineering Research Centers
www.eng.nsf.gov/eec/erc.htm

Engineering Research Center for Reconfigurable Machining Systems (University of Michigan)
http://erc.engin.umich.edu

Electronics Agile Manufacturing Research Institute (Rensselaer Polytechnic Institute)
www.eamri.rpi.edu