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Manufacturing Innovation and American Industrial Competitiveness

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An erosion of manufacturing capacities has contributed substantially to America's trade problems. The difficulty lies not in U.S. machines and technology, but in U.S. strategies for automation and the goals American firms seek to achieve through production innovation. Mass production and administrative hierarchies created the basis for American industrial preeminence in the years after World War II. There is substantial evidence that American firms have been unable to adopt or adapt to the production innovations emerging abroad. A sustained weakness in manufacturing capabilities could endanger the technology base of the country.

A GROWING DEBATE ON AMERICAN COMPETITIVENESS AND productivity has focused attention on manufacturing and manufacturing innovation (*1*). The scale and composition of the trade deficits of the past few years are the most prominent indicator that the competitive position of the American economy is weakening (*2*). The debate is about why the deficits have developed and what they mean. Our position is that much of the problem lies in an erosion of American manufacturing skills and capacities. If our position is correct, traditional economic remedies cannot in themselves reverse the decline in America's position in the international economy.

The huge trade deficits of the 1980s were driven by sharp increases in the value of the dollar that priced American goods out of world markets and made imports a bargain. The inflow of funds to finance the budget deficits pushed the exchange rate up. Consequently, some economists argue, the problem is fundamentally one of mistaken domestic macroeconomic policy. The process that created the trade deficits is reversible: reduce the budget deficit, thereby reducing demand for foreign borrowings to finance it, thereby reduce the trade deficit. To us this view is not so much wrong as it is limited and limiting.

Fifteen years ago this traditional remedy worked; devaluation rapidly reversed trade flows. This time, however, it has not, at least not as expected. Since 1985, the dollar has lost about half its value against the yen, but the trade deficit has stubbornly refused to follow suit. Only at the end of 1987 was a monthly decline first registered: the deficit fell to $13 billion, itself a record just a few months earlier. Certainly there is some price for the dollar at which imports would dry up and exports explode—if people had confidence that the exchange rate advantage would last. But balancing our external trade account is not the only objective. All nations, even the poorest, eventually do. The trick is to do it with high and rising incomes: that is the definition of national competitiveness (*3*). A permanently falling dollar translates into a continually impoverishing America. Clearly something new is affecting America's position in the international economy. What is it?

First, we have new competitors. The most important are Japan and Asia's newly industrializing countries. Japan's trade pattern is different from those of other advanced economies, for which intrasectoral trade has been the key to open trade. Japan uniquely has tended not to import in those sectors in which it is a major exporter (*3*, tables 8.1, 8.2, and 8.3). Second, the currencies of the Asian newly industrializing countries with whom we run major trade deficits have not risen against the dollar to the extent that the yen and European currencies have.

Most important, the United States once had dominant positions in product and production. We made products others could not make or could not begin to make competitively. Consequently, high wages and a high dollar did not displace us from markets. That situation has changed. In more technical terms, the price elasticities of American imports and exports have changed (*2*).

In the past 2 years the soaring yen has confronted Japan with a currency shock similar to the one we faced in 1981. A comparable percentage rise in the dollar flattened U.S. industrial investment and

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created massive trade deficits. But despite a doubling of the yen against the dollar, and a set of special emergency measures aimed at increasing imports, the Japanese increased investment in production and have sustained a trade surplus.

Why are the American and Japanese responses to massive currency movements so different? The contrasting behavior of the two economies in analogous situations suggests different efforts and capabilities to respond to economic challenges through innovation in manufacturing (*4*).

Determined Japanese firms attempt to increase productivity and flexibility and introduce new products as a means of defending market position. Certainly many Japanese firms have absorbed yen increases, often out of exceptional profit margins that resulted from a combination of U.S. quotas on imports and Japanese production advantages. And some costs are reduced as a strengthening yen lowers import costs of raw materials and components. A year ago major firms announced that they would remain competitive from a Japanese production base even if the yen rose to 120 to the dollar, whereas in some segments of electronics the principal Japanese firms could remain competitive with the yen at 90 to the dollar (*5*).

We must not lose perspective. Not all Japanese producers are that good, and not all production activities lend themselves to such dramatic improvements. Japanese firms are also moving production offshore, although capacities for production innovation remain great. However, there is little belief in Japan that moving off-shore to produce in a cheaper labor environment is a viable long-term solution.

Yet another view of the trade deficit is that the problem is not one of American firms, which know perfectly well how to produce and compete, but of America as a production location (*6*). The inference, quite at variance with the argument advanced here, is drawn from data on the export performance of American multinational corporations. Between 1966 and 1977 American multinationals increased their share of world exports, maintaining it through 1983 while the American national share dropped. There are major problems with the inferences drawn from the data. First, much of the data represents automotives and aeronautics. But despite the high exports automotives generate from various countries, the competitive positions of Ford and General Motors have weakened since 1966. Nor are sales of military aircraft the best indicators of economic efficiency. Boeing, the dominant company in commercial aircraft, operates less as an American multinational than as an American domestic producer that exports substantially. This correction aside, America's competitive position in commercial aircraft is weaker now than it was in 1966. Airbus has become a major competitor; Japan is building an aircraft industry, in part as a subcontractor to Boeing, while established European companies and upstart Brazilians produce short-range specialty craft.

But most important, in these and other sectors, what does it mean that American multinationals export so much from diverse locations? Those export numbers could be as much a sign of weakness as of strength. They could indicate decisions to manufacture components, subsystems, and even final products in various cheap labor locations abroad and export them back to the mother company in the United States—perhaps the company has failed to innovate in manufacturing and no longer has the skills to produce competitively in high wage locations. The U.S. consumer electronics industry exhibited that kind of busy export performance as it was being sliced down by Japanese competitors who operated from a base that included rapidly rising wages, rapidly rising productivity, and a trajectory of innovation in production that proved decisive.

In sum, inferences drawn from the export performance of American multinational corporations do not undermine our proposal that there is an important link between America's competitiveness problem and our difficulties in manufacturing innovation.

Organizations and Use of People

At the core, we propose that American difficulties in sustaining manufacturing innovation lie not in our machines and technology, but in organizations and the use of people in production, in the strategies for automation and the goals we attempt to achieve with production innovation. The problem is not with our robots or our local area networks, but with our understanding of how to exploit their productive promise. In the first part of the century, American firms built the model of advanced production. What went wrong? How did we fall from our position of leadership?

Here we must simplify a very complicated story (*3*). In the late 19th and early 20th centuries, the United States developed an industrial structure that projected this country into global economic preeminence. That structure rested on two fundamental innovations: mass production and the hierarchical, multidivisional corporation.

Mass production began in the early 19th century with production of interchangeable parts for guns; with Henry Ford's production of automobiles it became the model of how to produce in an advanced economy. It meant volume production of standardized products for a relatively homogeneous market. Volume allowed the specialization of tasks, both for machines and people. Moderately skilled workers, moreover, could produce sophisticated products.

The organization of people and machines turned on an underlying concept of how to produce. The concept was variously labeled Taylorism, for the management of people, or Fordism, for its market and production strategy. The hierarchical but divisionalized corporation, likewise, emerged in the United States to permit administrative control of complex activities on a continental scale (*7*).

During World War II and in the years that followed, this American system of management and production conquered the world. At home, the system defined the lines along which technological advance would proceed, and technological advance steadily improved the system's performance. Despite new technologies and new industries developing during the past 40 years, the basics remained entrenched until challenged by foreign competitors using different approaches.

Why, then, did the system freeze? First, many sectors such as automobiles and steel became stable oligopolies with only marginally increasing demand and high barriers to entry. These structures tended to divert competition from production costs or basic technological development to marginal product, process, and style changes. Also, complex social structures have resilience and inertia. The production structure developed elaborate systems of labor relations and comparably complex systems of management training, recruitment, organization, and reward. Massive forces had structured themselves around the basic design of that production system. Changing it would mean changing them. Finally, there was the inescapable fact that the system worked. It won the war; it won the peace. It was successful beyond any precedent or any contemporary comparison, and it could be steadily improved (*7*). The mass-production paradigm was not going to change without outside pressure. Suddenly we were vulnerable to innovation from abroad.

Innovation from Abroad

The innovations that emerged from abroad took two forms. One involved nationally distinct government policies for managing advanced industrial economies, policies that favored investment over consumption and allowed government's direct participation in the protection and promotion of industrial development. The second, the central part of our story, came in manufacturing and more broadly in the organization of production. During the post-war period, the gap between America and its allies closed. Yet while attempting to imitate American practice, firms and governments abroad established distinct manufacturing systems that suited their economic circumstances and social settings. Later, as world markets changed, and as technology gaps among advanced nations narrowed, the newly established models of production proved to have significant advantages.

The emblematics of these production innovations are code words such as "just-in-time production" and "quality circles," which at once suggest and obscure concrete changes in the way goods are designed and produced. The innovations in the best firms extend beyond the shop floor to the nature of the product, beginning with a design concern for manufacturability and extending to a corporate strategy in which anticipated economies of scope can justify investments in new technologies that are difficult to justify through more traditional criteria, but that figure in the firm's strategic positioning against its competitors.

Production in Japan and Italy

At present only limited systematic evidence exists to demonstrate that production organization differs sharply between countries, let alone that those differences are crucial to the success of firms. For now we find only clues drawn from narrower research projects. First we look at two images of production, one from Japan and the other from Italy. We use the word "image" intentionally, because the images are more suggestive than the models are robust and complete. From Japan emerges the picture of the high volume, automated factory operating through the night with no lights and no workers. The Japanese are not simply copying American production with less expensive capital or even pushing the American model of mass production to its logical conclusion. Something quite different is happening. For example, as part of a general reorganization of production, Japanese producers have reduced inventories and improved materials flows as well as altering quality control processes and substantially reducing labor content.

The important outcome is that the relation between production and corporate strategy is altered. Manufacturing becomes a competitive weapon. The evidence is overwhelming that low cost has not been the only or the most important advantage of Japanese production innovations. The Japanese did not invent the color television, the video tape recorder, or the semiconductor. But they developed designs and manufacturing systems that created decisive competitive advantage. It was not Japanese advances in the design of microchips, but in the yields of the production systems, that have made them the largest microchip producers and exporters in the past 5 years. Equally important have been their innovations in the organization of production, which permit them to introduce new products rapidly and constantly to improve and adapt the workings of that system. Honda defended its market position in motorcycles in Japan by abruptly introducing an entire new product line. The product cycle from design to production for Honda automobiles is faster than any foreign rival's (*8*). American producers, in contrast, typically do not make production innovations incrementally. They tend to jump from one production plateau to another; change is slower and riskier (*9*). Japan's flexibility has developed from continuous production innovation, often with internal design of equipment and a skilled work force able to understand and implement the continuous changes. Advanced production technologies are not an alternative to skilled workers. It is the capacity to manage the continuous evolution of the production system, and not merely the ability to operate an automated factory, that is the competitive meaning of post-industrial manufacturing.

Japan is not the only source of production innovation. In Italy networks of small firms have developed a different approach to innovative production organization, that of flexible specialization. Using modified traditional technologies, communities of small firms have established themselves as world-class producers in sectors such as textiles, apparel, and machine tools. These horizontal networks involve shifting combinations of cooperation and competition, with today's collaborators being tomorrow's competitors. Similar networks of world-class machine tool firms are found in Germany as well, suggesting that the model is not purely Italian.

The horizontal model of Italy and the vertical or Japanese model differ greatly from one another. Yet they share some common features. One of these is to limit inventories. The need for inventories is radically reduced, not just because some inventories are pushed back to suppliers, but because all producers in the chain learn to modify production to limit their own inventory needs. A second common element is a network of small suppliers tied to common tasks by market relations and direct hands-on contact rather than by administration and bureaucracy. Those fluid networks give flexibility to small and large companies alike. Some of the networks are vertical, with tiers of suppliers linked to large firms such as Fiat and Benetton in Italy or Toyota in Japan. Others are horizontal networks. These networks, these steps toward vertical disintegration of production, were not created deliberately. Rather, in Japan and Italy hordes of small producers survived, in part through political protection, into the late 20th century. As a result, small firms account for more manufacturing in Japan and Italy than in other advanced countries. The networked system was created as producers, large and small, sought ways of competing in national and global markets in the 20th century. The pattern differed from that established under American conditions. The networks proved more flexible, and resolved problems that traditional administrative integration could not.

Rapid expansion, in Japan, and in a less steady way in Italy, permitted capital investment and the introduction of new machines, and in the effort to catch up to more established technologies forced iterative production innovation. Introducing new machines opens the possibility of production reorganization, but does not ensure it (*10*). Nor do new production systems ensure increased productivity. Indeed, new production systems rarely function perfectly when first introduced and initially may lower productivity. Yet rapid growth generated not only investment in new machines, but also new approaches to manufacturing, new organizations to implement them, and new strategies to gain advantage from them (*11*). The innovations that initially were ways of competing in a world in which America's allies were laggards became unexpectedly the basis of advantage.

Flexibility in Manufacturing

Basic approaches to manufacturing are changing. An effort is being made to create the concepts and language to examine and discuss these changes, and flexibility is the code word (*12*). Traditional mass production is inherently rigid. It rests on volume production of standard products or components with specialized machines dedicated to specific tasks. Now the notion is to apply a set of more general-purpose tools to produce a greater range of products. Importantly, the bulk of manufacturing has involved batch production that was difficult to automate. Now new approaches and programmable equipment open batch production to increased automation, and reduce some of the cost difference between batch and series production.

Flexibility, a firm's ability to vary what it produces, rests on organization. The same machines can be used in rigid or flexible automation. Technology itself is channeled and formed by the conceptions of those who would use it. However, flexibility is an imprecise objective as much as a description, and has come to mean not one, but a variety, of ways to adjust company operations to shifting market conditions. Static flexibility suggests that a firm has the ability to adjust operations at any moment to changes in the mix of products the market is demanding. If one product is not selling, can production be oriented quickly to another? It implies adjustment within the confines of established products and a fixed production structure. This notion is captured in the distinction between economies of scale and economies of scope. Economies of scale is the notion that the cost of producing a single unit declines as volume increases. Economies of scope are gained not in the volume production of a single good, but in the volume production of a set of goods (*13*). Scope and scale often move together: large-scale plants may be required to realize flexibility. The advantages of scale do not disappear. Very expensive production lines make possible the volume production of a variety of products. In some industries, such as semiconductors, the cost of a basic production line has risen steadily even while application- and user-specific products have become possible. Economies of scope are created by standardizing processes to manufacture a variety of products.

Dynamic flexibility, in contrast to static flexibility, means the ability to increase productivity through improvements in production processes and product innovation. The capability to change quickly in response to product or production technology—to put ideas into action quickly—is the central notion. In a period when automation technologies permit new production strategies, dynamic flexibility is crucial (*14*). Yet as Jaikumar points out, making flexibility and responsiveness the mission of manufacturing "flies in the face of Taylor's view of the world which for 75 years has shaped thinking about manufacturing" (*15*).

The Infrastructure of U.S. Production

Is American industry capturing the possibilities of new technologies, or is it caught in an increasingly obsolete production paradigm? The evidence, which by its nature is fragmentary, comes in two forms. The first is a large set of industry and firm case studies of international competition and production organization. These cases are more than anecdotes, for taken together they represent a substantial share of the economy and tell a consistent story, a story of slow and partial adjustment. In steel, American firms import from Japan production know-how that was based on an earlier Austrian innovation. In automobiles, American firms struggle to match the cost and quality performance that has enabled Japanese firms to capture a large, permanent share of the American market. In both sectors the recent drop in the dollar's value has closed the gap in final costs, but has not placed American firms on a competitive trajectory of technology development.

The semiconductor industry recently was shocked to discover that its seeming technological advantage was vulnerable to production developments in Japan. The production tools that embody know-how and innovation—machine tools in metal bending industries, automatic looms and jet spinners in textiles, photolithographic and ion implantation equipment in semiconductors—increasingly are imported. One offshore producer of apparel argues that, on paper, the economies permit him to bring production back to the United States, but the required skills and infrastructure no longer exist. They can be found in cheap labor locations. It is not simply that a set of firms or sectors are in difficulty, but that the infrastructure of production know-how has weakened. A change in relative prices achieved through changes in exchange rates will not quickly reverse this erosion.

In the late 1960s and early 1970s, American firms faced with foreign competition often concluded that their rivals used low-cost labor to achieve competitive advantage. Few firms realized that innovations in production, usually achieved with limited technological advance and considerable organizational imagination, were occurring. The flight of American firms offshore to low-cost production sites represented, finally, a means to defend existing production structures. It sheltered firms from the need to rethink their own production strategies.

If our argument is correct that American industry is not effectively implementing the potentials of production innovation, what additional forms of evidence should we expect to find? First, the ways America uses advanced technologies would differ from ways our best competitors use them. American firms would not capture the full potential of new technologies: rather than creating flexible systems, they would implement new technologies in traditional ways. Second, advanced technologies for innovative production would not diffuse as widely in the United States. Standard data sets for measuring economic activity do not address the question of production organization. Large-scale comparative studies that would directly test our notion do not exist. Yet there are narrower, more limited studies that support the argument. Let us consider two such studies.

Use of New Technologies

The first question is how new technologies are used. One recent study compares the use of flexible manufacturing systems (FMSs) for the production of comparable products in Japan and the United States. The average number of machines in the Japanese FMS was six, and in the American system seven (*15*, p. 69). However, "the number of parts made by an FMS in the United States was 10; in Japan, the average was 93, almost ten times greater. . . . The annual volume per part in the United States was 1727; in Japan only 258" (*15*, p. 10). The Americans used the tools as instruments of an old-style approach to manufacturing. They also failed to exploit them for introducing new products. The rate of new product introduction was 22 times as great in Japan as in the United States. Jaikumar concluded that, with few exceptions, the flexible manufacturing systems installed in the United States show an astonishing lack of flexibility in use, in many cases performing worse than the conventional technology they replaced. "The technology itself is not to blame. It is the management that makes the difference" (*15*, p. 69).

The risk is that the social inertia of existing arrangements locks American producers into reinforcing rather than replacing existing production systems. A few examples give a sense of the situation. General Motors invested $50 billion in production during several years only to discover that its margins were the lowest in the industry, its break-even volume point was the highest, and that no clear production strategy had emerged (*17*). The purposes of automation and the organization suited to capture the advantages of new technologies have not been worked out in many American firms; thus new technologies are not introduced or have limited impact when they are.

The second dimension is the diffusion of advanced technology. Arcangeli *et al.* examined the introduction of advanced automation technology into factories in advanced countries (*18*). Their techniques and data sought to separate advanced from traditional manufacturing investment. Two conclusions are suggested. First, the United States leads the way in office automation, but trails in factory automation. Second, America invests more in traditional automation and less in flexible manufacturing than do other advanced industrialized countries. The pace at which advanced technologies are introduced is slow—that is, only a small percentage of firms use such things as flexible manufacturing systems. Yet those American firms that use them tend to be leaders in their sectors. These data are consistent with studies of specific technologies, such as robots. Numerically controlled machine tools and the advanced languages to implement them emerged early in the United States, as did the technology and use of robots. However, as is widely known, they are used much more extensively in Japan than in the United States; diffusion is several time broader, with some 40% of the machines in smaller firms (*14*).

The evidence is powerful. Aggregate trends reinforce factory and sector studies. The argument that there is a problem in the evolution of American manufacturing is now strong enough to require refutation rather than demonstration.

Despite the disturbing past, there is no reason that these trends must continue. The picture is complex and changing. Many American firms have begun to innovate in production organization. Allen Bradley, Black and Decker, Cypress Semiconductor, Texas Instruments, and IBM all provide examples. It is not yet possible to judge whether there is new life in American industry or whether the successes are "valiant but isolated." The future is being created, and the outcomes are inherently not knowable (*16, 19*). The more systematic data, however, suggest that the difficulties outbalance the advances. Jaikumar summarized the problem well: "The battle is on and the United States is losing badly. It may even lose the war if it doesn't soon figure out how better to use the new technology of automation for competitive advantage. This does not mean investing in more equipment; in today's environment, it is how the equipment is used that is important" (*15*, p. 70). A "manufacturing gap," the counterpart of the technology gap of earlier years, has emerged, and this time it is the United States that lags behind.

Conclusion

We have tried to show that weakness in production innovation is central to America's competitiveness and trade problem. For a firm, production capability is a decisive competitive tool. It is not just a question of marginal cost advantages; a firm cannot control what it cannot produce competitively. There is little chance of compensating for production weakness by seeking enduring technological advantage (*3*). A production disadvantage can quickly erode a firm's technological advantage. Only by capturing the "rent" on an innovation through volume sales of a product can a company amortize its R&D costs and invest in R&D for the next-generation product. The feeble American presence in next-generation consumer electronics indicates the cost of failure to produce competitively in the previous generation. Finally, if a firm simply tries to sell a laboratory product to someone else to produce, the value of the design is lower than that of a prototype, and prototypes are valued lower than products having established markets, as each step toward the market decreases uncertainty. A producer with a strong market position often can buy a portfolio of technologies at a low price and capture the technology rents through volume sales. For the firm, manufacturing matters.

Mastery and control of manufacturing is equally critical to the nation. This fact, so central to policy-making, has been obscured by a popular myth that sees economic development as a process of sectoral succession. Economies develop as they shift out of sunset industries into sunrise sectors. Agriculture is followed by industry, which in turn is sloughed off to less developed places as the economy moves on to services and high technology. Simply put, this is incorrect. It is incorrect as history and it is incorrect as policy prescription. America did not shift out of agriculture or move it offshore. We automated it; we shifted labor out and substituted massive amounts of capital, technology, and education to increase output. Critically, many of the high value added service jobs we are told will substitute for industrial activity are not substitutes, they are complements. Lose industry and you will lose, not develop, those service activities. These service activities are tightly linked to production just as the crop duster (in employment statistics a service worker) is tightly linked to agriculture. If the farm moves offshore, the crop duster does too, as does the large-animal vet. Similar sets of tight linkages—but at vastly greater scale—tie "service" jobs to mastery and control of production. Many high value added service activities are functional extensions of an ever more elaborate division of labor in production. The shift we are experiencing is not from an industrial economy to a postindustrial economy, but rather to a new kind of industrial economy.

The choices we make now will shape our future. We cannot simply imitate our most successful competitors, although we must learn from them. Just as new and innovative industrial solutions emerged abroad in response to American industrial success, so we must create our own innovations in response to new pressures. The innovations, moreover, will emerge incrementally. There will be no simple formulas, no one magic trick. Our choices, moreover, are sharply limited by a set of constraints and opportunities. In our view there are three principal constraints. First, as a nation we cannot compete in world markets by cutting wages. Not only will it not work because there are many willing to work at wages forever lower than those that we can pay, but also it would mean a total and catastrophic change in our society. Happily there is substantial evidence that a highly skilled work force can sustain the productivity and value added required to be a highly paid one. Second, a retreat to defensive protection will not serve as a long-term policy to sustain high wages and productivity. Third, policies that are radically inequitable are unlikely to generate the broad political support required for a national commitment to long-term growth and innovation.

The opportunities are equally constricting. Ours is a world in which science and technology, capital, and management know-how are widely available. Consequently, our international competitiveness is based on how effectively we develop and diffuse technology and product and production know-how to our firms and how effectively we use those technologies. Effectively using those technical possibilities depends on management vision and worker skills. Simply put, in the long run investment in science, in technological development and diffusion, and in education is all that will sustain us.

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Free-Electron Lasers

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Free-electron lasers are tunable, potentially powerful sources of coherent radiation over a broad range of wavelengths from the far-infrared to the far-ultraviolet regions of the spectrum. These unique capabilities make them suitable for a broad variety of applications from medicine to strategic defense.

FREE-ELECTRON LASERS REPRESENT A COMPLETE DEPARTURE from conventional lasers, with properties and problems all their own. Making use of a simple and elegant gain medium—an electron beam in a magnetic field—they have already demonstrated broad tunability and excellent optical-beam quality. In the future they may generate the greatest average power ever achieved by a laser.

"Free" electrons are electrons that are not "bound" into atoms or molecules. The electrons in a free-electron laser form an electron beam in a vacuum, much like the electron beam in the picture tube of a television set except with much higher energy and intensity. Electrons bound to atoms and molecules vibrate only at specific frequencies. Thus, the laser light from conventional lasers, which make use of bound electrons, appears only at the frequencies specific to the atoms or molecules of the laser. On the other hand, the electrons in free-electron lasers are forced to vibrate by their passage through an alternating magnetic field. The vibration frequency, and hence the laser wavelength, can be adjusted by altering the construction of the magnetic field or by changing the speed (or energy) of the electrons passing through the magnetic field. There is great interest directed to free-electron lasers because of their broad tunability from the far-infrared to the far-ultraviolet. Recently, it has been recognized that free-electron lasers are uniquely suitable for operation at very high average power levels, and this has made them attractive for military applications.

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Historical Overview

Because they depend on an electron beam in a vacuum magnetic field, free-electron lasers actually have as much in common with microwave devices as they do with conventional lasers. For this reason, they can be regarded as an extrapolation of microwave technology to optical wavelengths. In fact, the first device to have the characteristics of a "free-electron laser" was operated in the microwave portion of the spectrum. It was not known as a free-electron laser, since at that time lasers had not yet been invented.

Free-electron lasers as we know them today were actually developed independently, as an extension of synchrotron radiation research. Synchrotron radiation is the short-wavelength radiation that is given off by electrons in synchrotrons and storage rings. This radiation can be enhanced by adding magnets to a storage ring to wiggle the electrons, with the magnets arranged in the same configuration now used for free-electron lasers. The synchrotron radiation from such wigglers (or undulators) is identical to the incoherent, spontaneous radiation observed from free-electron lasers before they begin to lase.

The earliest work on wiggler or undulator radiation dates back to 1951 when Motz (*1*) demonstrated incoherent radiation from such devices in both the millimeter and optical regimes (*2*). After this work, Phillips, then at General Electric, developed a device he called