Science and Product

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Recent events on the industrial scene have shown that scientific leadership, even leadership in discoveries such as the transistor or in biotechnology, does not necessarily translate into industrial or product leadership. This fact is less surprising when we realize that the United States was the world's economic leader in the 1920s, at a time when we were far from being the leading scientific power. If we are to understand why the United States can continue to dominate in the generation of new scientific ideas, but not necessarily succeed in the development of competitive products, we need to think more concretely about the connection between science and product.

The transistor exemplifies one type of connection. This device was certainly science-based. Its first crude forms were the result of a gradual buildup of fundamental knowledge about quantum mechanics and solid-state physics since the 1920s. Step by step, the crude forms became increasingly usable devices. We will call this step-by-step reduction to practice of a new idea the "ladder" process. In this process, a new idea or technology dominates, and a product is created around it. Those who understand the idea or technology best, often scientists, play the most important role.

However, there is another procedure that we will call, in contrast to the ladder, the process of cyclic development or repeated incremental innovation. By this process, an existing product is improved and is provided with new features year after year. Although the process is evolutionary, the cumulative effect of these incremental changes can be profound.

Incremental Product Development

It is this process of incremental innovation or incremental improvement that, after the initial ladder-style invention of the transistor, has given us better computer memories every year. In the last 20 years the number of bits on a chip has gone from one to one million. Incremental improvement has also given us better resolution screens and quieter and better quality printers each year. It has given us jet engines with double the thrust per unit weight of two decades ago, plastics that can be used at temperatures twice as high as a decade ago, and incandescent light bulbs that are 15 times as efficient as Edison's; in short, an array of products across the entire spectrum of modern industry that are much better, and often less costly, than those of an earlier era.

Most products sold today were here in slightly inferior form last year, and most competition is between variants of the same product. Competition usually involves my auto against your auto, not my auto against your helicopter. In technological areas where the United States has not been competitive, we have lost, usually not to radical new technology, but to better refinements, better manufacturing technology, or better quality in an existing product.

An important point about incremental development is that it is a process built around the existing product—not, as in the ladder process, around a new idea. The people who know the existing product best, and who decide what happens next, are the people already working on that product. How they improve the product is strongly affected by its existing form.

Incremental development is also cyclical. In the world of computers, printers, jet engines, or medical imaging devices, when the current version of the product is in the manufacturing phase, a development team is working on the next product generation. And when that next generation goes into production, the following generation is started through the development process. For example, the manufacturing division could be making 256-kilobit memory chips, while the development department is working on refining the tools, the process, and the design for a 1-megabit chip. When it is ready, the megabit chip is introduced into the manufacturing division, which gradually builds up production and phases out the 256-kilobit chip. Then the development process starts again on a 4-megabit chip.

The speed of this development and manufacturing cycle is vital. If one company has a 3-year cycle and another has a 2-year cycle, the company with the shorter cycle will have its process and design into production and the product in the market 1 year before the other. The firm with the shorter cycle will appear to have newer products with newer technologies. In fact, both companies will be working from the same storehouse of technology. It is the speed of the development and manufacturing cycle that appears as technical innovation or leadership. It takes only a few turns of that cycle to build a significant product lead. This consequence is as true for long-cycle businesses such as aircraft engines as it is for short-cycle ones such as microelectronics.

A key factor in the speed of the cycle, as well as in the quality and cost of the product, is the closeness of the tie between development and manufacturing. Design for easy manufacturability leads to rapid introduction into and buildup in the manufacturing stage. Close ties between development and manufacturing translate into early knowledge of technical problems, into speed of market introduction, and also into quality, because the product is easy to manufacture. A lack of close ties has the opposite effect.

Another significant feature of the development and manufacturing cycle is its relative imperviousness to ideas coming from outside itself. Although this is sometimes described as the NIH (not invented here) syndrome, real as well as psychological factors are involved.

First, there is a right moment to get a new idea into the cycle from

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the outside. An idea must be proposed at the beginning of the cycle; halfway through is too late. A better printer head proposed 1 year into a 2-year development cycle is useless. Second, the new idea, the new printer head, for example, must be reasonably well developed and tested. The development team must be able to finish the next product cycle in time, and not have its schedule altered by a morass of unforeseen problems as the details of the new idea are worked out. A third complication is that the product is often too complicated or uses processes too complex to be completely understood. Examples of such complex processes are electroplating baths whose composition or component effects are not known, complex reactions with ions in a plasma on surfaces, or even the vibrations affecting the flight of a read/write head over a data storage disk or a turbine blade in a jet engine. Often in development and manufacturing, one does not know exactly how something works, only that it worked the last time. In this situation, small evolutionary changes are more acceptable than large radical ones.

These considerations all weigh heavily against ideas from the outside, and even more against outside ideas at a university research level of development. If new ideas are difficult to get into the cycle from the outside, then those who are in the cycle and who understand the current state of the art in detail must be the bearers of new ideas. This means that the product engineers must be aware of the relevant science and technology because they often provide the only incoming route for new ideas. If they are not knowledgeable about what is happening technically in other companies or in universities, a high level of technology in the world around them will go to waste, or more likely, be seized by a competitor.

Competition from Japan

Our effective foreign competition to date has been characterized by close ties between manufacturing and development, an emphasis on quality, and the rapid introduction of incremental improvements into the short development cycle of a preexisting product. There has also been a consistent and effective effort, by those in the product cycle, to keep informed on the relevant technologies and on what is going on in the technical world, in the university world, and in the competitor's product. In particular, Japan has performed in a superior manner in technology-based industrial development over the last several decades. Their story is well known, but what has caused this success?

Conventional wisdom says that the Japanese prowess in technology comes from several key factors. First, mediated by their Ministry of International Trade and Industry (MITI), the Japanese have collectively targeted certain industries. Second, again led by MITI, they have orchestrated precompetitive R&D in these selected industries. And third, they have vigorously pursued the acquisition of Western technology through licensing of patents and know-how. These well-known factors, however, are not the whole story, and they are probably not the main story.

During this enormously successful period of the last several decades Japan has never introduced the first product in any market on the basis of a significant new technical breakthrough. Transistors, integrated circuits, computers, fiber optics, lasers, computer tomography, magnetic resonance imaging, video recorders, and color television are among the many advances made in the West and first embodied in new products in the West. Yet in each of these areas the Japanese have subsequently gained a strong and sometimes dominant position. The strength of Japanese innovation includes three areas: manufacturing, design aspects of development, and the development cycle itself. Manufacturing has been dealt with at length elsewhere; we will discuss here design and the development cycle.

In the United States, the design phase of the cycle of development has traditionally concentrated on the features and performance of the product rather than on the processes by which it will be manufactured. We design the product first and then tackle the job of how it is to be made. Yet the eventual cost and quality of the product is inseparable from the way it is made. If a product can be made easily, its cost will be low and, most probably, its quality high. A complex product, with many features and elements for product performance, but designed without regard to the intricacies of making it, becomes a product of high cost, questionable quality, and uncertain reliability. Yet there has been a strong propensity in U.S. engineering to follow this course, a course that separates design and manufacturability.

By contrast, the Japanese are oriented to simplicity in their designs. After General Electric (GE) developed the fan beam, computed tomography system of medical imaging, its Japanese partner designed a simpler, lower cost version. The Japanese take a straightforward approach to design, whether in consumer electronics, autos, landscaping, traditional architecture, automation controls, or medical equipment. Their designs embody state-of-the-art technology and easy-to-use functionality in attractive designs, which tend to be manufacturable.

Although low manufacturing cost is a natural corollary of simple designs, the Japanese nevertheless also make it an explicit objective of design. In comparing prior designs of industrial controls with a new Japanese partner, GE found that its own engineers had, through successive design iterations, added feature after feature, whereas their Japanese counterparts had started with and met an inviolate cost barrier. The U.S. designer, starting with a certain tradeoff between cost and performance, proceeds through subsequent design changes to add features and performance, and ends up with higher cost. The Japanese designer holds to the designated cost; no matter how many design cycles there may be, the initial cost barrier remains inviolate. Japanese designs are not only strongly constrained by the cost of the original product but are also optimized to permit further cost reductions in successive generations of the product.

In addition, the Japanese are highly responsive to markets, but in a pragmatic way. In well-developed markets, their incremental approach to technology, to product innovation, and to design is well suited to respond to shifts in customers' reactions. Moreover, the linkage of markets, design, and technology is strongly enhanced by the career paths of typical Japanese engineers who move from function to function. In markets that are still undeveloped, the Japanese are willing to live with small specialty products for a time, while they refine the technology and the designs and learn something about the market itself through pragmatic experience rather than reliance on U.S.–style market studies.

Innovations in products, like advances in technology, occur step by step in Japan. The Japanese, generally, have not developed and designed the first wave of products based on frontier technology, any more than they have pioneered the technology itself. For example, in the semiconductor industry, they have lagged behind in such things as microprocessors and application-specific integrated circuits. But they excel at making incremental innovations based on steady, evolutionary advances in technology.

The Japanese effectively use this capability for incremental advance in the competitive arena. They will counter the introduction in the United States or another country of a new generation of products based on novel technology with the best that can be done with prior state-of-the-art technology, taking advantage of the lower cost of the old, well-practiced version to offset the higher perform-

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SV40 system, we repeated our reported experiments using isolated HL60 nuclei (*1*). The *myc* protein, after approximately 1 year of storage, no longer neutralized the inhibitory effect of the antibodies. Gel electrophoretic analysis showed altered properties which indicated partial degradation of these protein samples. Further purification of the polyclonal antibody to the c-*myc* recombinant protein, which was used in our previously reported experiments, reduced, but did not abolish, its inhibitory effect on DNA synthesis in this system.

These findings clearly raise the possibility that a component of the preparation other than the c-*myc* antitody inhibited DNA synthesis in the SV40 system. However, it ı also possible that a deterioration of the samples during the prolonged storage has been responsible for the results of the Roche workers. In this context, it should be noted that in a more recent study antibodies to c-*myc* from another source were found to inhibit DNA replication of an autonomously replicating plasmid containing DNA sequences derived from mouse liver when they were cotransfected into HL60 cells, or in an in vitro replicating system employing HL60 nuclear extract (*3*). Another group has reported that elevated c-*myc* expression facilitates the simultaneous replication of SV40 DNA in human lymphoma cells (*4*), which can be due to indirect or direct effects on DNA replication. Thus, further work seems necessary to resolve this issue in the light of these conflicting data.

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ance of the new. An example is their offering of an adjustable-speed motor drive, based on solid-state power devices already in volume production, to counter the introduction of a sophisticated variable-speed drive based on an innovative new class of power devices. Although the newer devices were the lower cost alternative at equal volumes of production, they incurred higher initial costs because of low start-up volumes. Moreover, increasing production to sufficiently high volumes for competitiveness was threatened by the market share captured by the admittedly lower performing, but still satisfactory, Japanese product.

The close tie, or often the lack of distinction at all, between the engineers engaged in manufacturing and those engaged in development is one of the many factors that contribute to a rapid development and manufacturing cycle. This short cycle in turn fits well with the exploratory approach to marketing. The Japanese company gets the product out fast, finds out what is wrong with it, and rapidly adjusts; this differs from the U.S. method of having a long development cycle aimed at a carefully researched market that may, in fact, not be there.

The intentness with which the Japanese learn what is going on in the rest of the world is legendary. They usually seem more willing than their U.S. counterparts to learn about and profit from what others have done. They appear generally to suffer less from the psychological aspects of the NIH syndrome, which often seems to debar U.S. engineers, raised and rewarded on individual creativity, from accepting the ideas of others. Less well known is the general openness of the Japanese to discuss what they themselves are doing. Japanese engineers, in our experience, are willing to talk and are steady participants in engineering society meetings, as presenters as well as listeners. Visitors to Japanese laboratories are impressed by the high level of knowledge in evidence there of the most up-to-date technologies and of events occurring in the rest of the technical world.

Finally, there is the issue of "persistence." In the United States, persistence is measured in months; in Japan, in years. In the United States, we expect breakthroughs to overcome adversity; in Japan, they expect persistence to do so. The Japanese believe more strongly in their incremental technical visions than in elaborate market studies. They worry less about foreseeing markets and more about being better than their competitors, believing that they will then never be at a competitive disadvantage, whatever directions the markets take. They let customers' reactions to existing products tell them how to change and improve them. The Japanese assume that in time they can work their way through any difficulty; therefore, they persist as long as the original goal remains valid. Building on the frontier technologies introduced elsewhere, and using them step by step to improve products, has brought Japan to a leading position in key product areas.

Conclusion

Much of what needs to be changed in U.S. industry involves close ties to manufacturing, design for manufacturability, a rapid design cycle, and up-to-date technical knowledge on the part of the engineers themselves. Being up-to-date requires conscious company effort. Traveling to meetings, reading the technical literature, and being a part of the engineering community are necessities if we are to compete with others who make these efforts and are thus better able to incorporate technical change rapidly into their own products.

Outside the product improvement cycle, a research (as opposed to development) organization in industry must have close ties to development and manufacturing in order to succeed. With these close ties, researchers can understand the progress of the cycle and can introduce new steps at the appropriate time and in an acceptable form. A research organization that surmounts the internal barriers and becomes an accepted contributor to the development and manufacturing process can, because of its greater technical depth, its scientific knowledge, and its close ties with the university world, become a forceful initiator of progress. It is more difficult, in our opinion, to make these contributions from a university base and from government laboratories as they are now constituted.

Much has been said by industry and government leaders about reforming the educational system and strengthening the national science base—things that help build a strong foundation. A strong science base supplies a vast storehouse of new ideas, and a good educational system provides engineers and manufacturing workers with knowledge; but strength here cannot make up for inadequacies in the functioning of the development and manufacturing cycle. The United States must learn to succeed, not only in the ladder type of innovation in which a wholly new idea from science creates a wholly new product (the science-dominated process at which we have succeeded in the past), but also in the rapid, cyclical, engineer-dominated process of incremental product improvement. Neither process is a substitute for the other; we need both.