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Scout for technology, design for manufacture, shorten the time to market.

From the 'Ladder of Science' to the Product Development Cycle

by Ralph E. Gomory

U.S. business needs to understand how science and technology influence industrial competitiveness. Even in high-tech products, like computer memories, the U.S. trade surplus declined sharply early in the 1980s, and we were in deficit by 1986. How could this be happening to the greatest scientific power in the world – the home of the most Nobel laureates and innumerable scientific breakthroughs?

Too often the discussions about remedies center on the wrong questions: Which country invests the most of its GNP in basic research? Who has the most engineers and scientists? And then there are various statistics about how U.S. corporations are still outspending Japan, our biggest competitor, on research and development and the disquieting reports about the large number of foreign students picking up advanced degrees at our universities.

In fact, the United States is learning only now the hard lesson it taught the rest of the world earlier this century: Product leadership can be built without scientific leadership if companies excel at design and the management of production.

The United States was the leading industrial power well before it became the leading scientific power. When, during the 1920s, the capitals of science were the European universities, the United States excelled in worker productivity and per capita income and had the biggest trade surplus – it was preeminent by almost any industrial measure. Now U.S. universities are the capitals of science, and Japan has the trade surplus.

Given current Japanese superiority in manufacturing technology, this may seem a grim message to U.S. managers. It is not meant to be, but rather should be the basis for cautious optimism. If Japanese companies are by and large competing more successfully than U.S. companies right now, they aren't doing anything we cannot learn.

Again and again I read about the radical "macro" changes Americans must make if our major corpora-

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tions are to regain their edge – a new, Zen-like attitude toward excellence, perhaps, rigorous new incentives for consumers to save money, a reformed system of basic education, a cultural merging of science with entrepreneurship. There are important insights and valid long-range directions implied by these rather sweeping demands, yet they miss the point. There is a great deal we can do now.

The *first* things high-technology companies should busy themselves with are doable "micro" changes in the way they manage the product development process. They should concentrate on comparatively small things – immediately doable things – like designing for manufacture, getting product into customers' hands more quickly, or pulling the right know-how into the development of products at just the right time. It is all fine and well to perfect the conditions that engender creativity. But technology-driven companies first have to organize to make the best fourth version of a product, not the best first. Often it hardly matters who made the first.

These urgent corporate tasks are very difficult, but they are not mysterious. If, on the whole, Japanese executives bring them off more successfully than we do nowadays, there is nothing inscrutable about their actions. Our fate certainly doesn't rest with business schools teaching about exotic new corporate culture. Once U.S. managers know what their companies are supposed to do, they too will work out the ways to manage their people. The point is to get clear what has to be done.

Two Concepts of Innovation

The Ladder. The most common, reasonable perception of the relationship of innovation to production is the step-by-step reduction to practice of new scientific knowledge that then generates a radically new product. The Manhattan Project springs to mind, or Du Pont's development of nylon. I think of the process as a kind of "ladder" because usable things come as the culmination of cumulative scientific research – as in nuclear physics or organic chemistry; the process then moves, step-by-step, toward increasing practicality. Science seems to yield what the Victorians called "progress."

While this ladder process goes on, those who understand the idea or technology best – most often scientists – play a leading role in shaping products. Their ideas dominate; the customers' needs are taken for granted.

When revolutionary commercial products emerge out of scientists' labs, they succeed by providing a great business opportunity. Windfall profit comes from doing what nobody else can. You are first, and you have what everybody wants or can be expected to want. You invent nylon, and you sell millions of stockings. If you could actually produce a cold-fusion reaction, you can expect to sell a great deal of electricity.

The first crude forms of the transistor, available by 1948, were the result of a buildup since the 1920s of fundamental knowledge about quantum mechanics and solid-state physics. Scientists descended the rungs to practical application. Crude transistors gave way to a series of increasingly usable devices, which started to appear in radios in the early 1950s. Finally, they found their way into computers. The transistor was essentially a new idea when scientists created the chip around it.

> The innovations of cyclic development may sound dull. When they win in the market, they are exhilarating.

The great ladders of science are by no means all in the misty past. We see reductions to practice today in molecular biology and perhaps superconductivity. Any company that is first to exploit these new technologies in unexpected ways can count on winning millions of customers worldwide for revolutionary products. For a short while, that company will not have to bother about competitors cutting into profits.

The Product Cycle. There is another, wholly different, less dramatic, and rather grueling process of innovation, which is far more critical to commercializing technology profitably. I call it, naturally enough, the "cyclic development" process, governed as it is by the product cycle. Its hallmark is incremental improvement, not breakthrough. It requires turning products over again and again; getting the new model out, starting work on an even newer one. This may all sound dull, but the achievements are exhilarating.

Many products, after going through the ladder process, are absorbed into cyclic development. Quite apart from features ceremoniously introduced to win new customers, a product's stuff is quietly improved. Year after year, refrigerators are changed; plastic replaces steel, glass becomes more and more resistant to breaking, compressors become more energy efficient. In this way, the engine that powered the Model T gave way, by generations, to the Quad-4. The computer chip became denser and much more powerful –

16 memory-bits 25 years ago, more than a million bits today.

There is no brand new product here, no revolutionary technology. Cyclic development is a competition among ordinary engineers in bringing established products to market. The contest is between my car and your car, not my car and your helicopter. Another way of saying this is that production is a relentless race, not a collegial puzzle. The company works assiduously to refine the product, customize it for more and more consumer segments, make it more reliable, or get it to market more cheaply.

To be sure, there are times when incremental improvements in one area of application suddenly become the solution for engineers stymied in a quite different area. Amorphous silicon had been developed and slowly improved in the production of solar cells. It was only after engineers had gone through several cycles of improvement in small liquid-crystal displays that they imported amorphous silicon into their work on very large displays. Amorphous silicon allowed them to deposit transistors inexpensively on the back of the display. Similarly, HDTV will merge more computer technology with established, many-times-refined ways of making televisions – a definite advantage for the Japanese.

I cannot stress enough that what ground U.S. consumer electronics and automobile producers have already lost *cannot* be attributed to failures of new science or to failures of innovation. We originated those industries and then fell behind in making refinements – behind the Japanese commitment to quality design and careful manufacturing, not behind in science and new ideas. If proponents of a U.S. industrial policy assume that Japanese competitiveness derives mainly from the Ministry of International Trade and Industry's targeting advanced technology for concentration and expansion, they are getting only part of the story right – and the smaller part at that.

MITI *has* orchestrated national research, such as the very large-scale integration project, and it has encouraged Japanese corporations to pursue Western technology actively. More recently, MITI has facilitated ladder-style innovation in such things as "fifth generation" supercomputing by funding and coordinating national research programs.

Too Much Support for R&D from Corporate Sources…

Source of R&D Funds:	Corporate Labs and Technical Centers	Group, Sectorial, and Divisional Labs
Corporate	50.3%	23.1%
Business Units	41.1%	70.7%
Transfers from Other Labs	0.7%	0.8%
External to Company	7.2%	3.4%

…Too Little Support for Process R&D

Percent of Technical Effort Spent on:	
Basic Research	>1%
Applied Research	23%
Product Design, Development, and Engineering	34%
Process Design, Development, and Engineering	23%
Technical Service	20%

Charts supplied to HBR by Center for Innovation Management Studies at Lehigh University. Responses are drawn from questionnaires sent to R&D executives in the 210 U.S.-based companies comprising the membership of the Industrial Research Institute.

To compete better, U.S. companies must reform their approach to cyclic product development through greater emphasis on process technology and must better integrate R&D with other company divisions. These charts show that both could be improved.

And yet I have trouble thinking of a single product Japanese companies have introduced first – one that sprung from their own basic research in new technology. Their strength is not science. Our weakness will not be cured by doing better science. We must reform the way we approach cyclic product improvement. In the key industries that are problems today, we have been good starters, the Japanese have been good finishers.

The Hard Facts of Cyclic Development

Most development work is done *just one step ahead of manufacturing.* While the company's plants are making the 256K chip, R&D is working on designing, refining, and processing the 1-megabit chip. When the 1-megabit chip is ready, manufacturing ramps up, increases volume – and the 256K chip is phased out. This triggers development work on the 4-megabit chip so that the process can start all over again. This pattern appears in all kinds of manufacturing – cars, consumer electronics, jet engines.

One cannot overestimate the importance of getting through each turn of the cycle more quickly than a competitor. It takes only a few turns for the company with the shortest cycle time to build up a commanding lead.

Even if a company starts out with an inferior product, it can overtake the industry leader if it has the capacity to turn out a new line 6 to 12 months more quickly. Our Japanese competitors believe that, in the shortest of long runs, quick development beats market research every time. I once made the mistake of asking a Japanese colleague, my counterpart in an electronics company, whether he had researched how customers were likely to respond to a particular kind of ink jet for printers. Why, he politely retorted, should he study whether customers are *likely* to respond positively to this or that jet if his company can get out a wholly redesigned printer in a year to 18 months? Why not adapt to actual buying patterns? (Why, he implied, should I be bothering with such questions?)

Moreover, people often observe that company engineers tend to be *impervious to ideas from outside sources.* R&D people often call this the not-invented-here syndrome – an inappropriately psychological phrase to describe an objective difficulty. By common prejudice, the resistance of designers to new ideas is ascribed to a certain mental inertia: we tend to think of the resistance of U.S. car designers to disc brakes, radial tires, and computer-governed, electronic fuel-injection systems; or of how long it took consumer electronics companies to replace metal parts and casings with molded plastics.

The facts are that design engineers cannot easily work with newness and keep to their timetables. Engineers need new ideas that snap into the skills they already have. They want to use the tools they've mastered. They want to finish in 18 months. Perhaps the hardest kind of knowledge for engineers to absorb is work done at research universities – work that is potentially useful but that appears to them at an early stage of development or that simply is packaged in a form alien to the product team.

Product development has a timetable that cannot be interrupted to accommodate some unexpected piece of technology. A better print head proposed for a printer one year into a two-year cycle is useless. New solutions, however sweet, *have to be available to designers at the beginning of the cycle.* Halfway through is too late.

Incidentally, even at the start of the cycle, new ideas are useful only if they've been pretty well fleshed out and tested so that the development team can incorporate them without breaking stride. R&D can rarely afford to see the schedule slip over the details of a component. Few incremental changes are significant enough to warrant being beaten to the market by competitors, which would mean losing business, revenue, customer loyalty. You don't risk losing a part of the base from which to compete next time around.

Tie Design to Manufacturing

Since design is one step ahead of manufacturing in the race to the end of the product cycle, one of the most important challenges for high-technology managers is to get manufacturing expertise contributing directly to product development early on. American companies have to give far more attention to design for manufacture.

In the United States, a kind of caste system has emerged in product development. Design engineers are focused on product features and performance, which have more prestige in the engineering world. Manufacturing people are mired in the grim and gritty details of production – in intermediate costs, in the ways components are actually put together. ("We've built one," says design to manufacturing, "now you build 10,000.")

Nothing could be further from Japanese practice, where design specialists and manufacturing people work side by side, often in product teams, so that the designers will be more cost-conscious and oriented toward manufacturing simplicity. Japanese design engineers typically start out their careers in manufacturing plants, so they're intuitively thinking about the control processes that are needed to maintain consistently high quality.

Without manufacturing's early participation in design, latent production problems are bound to remain obscure. Product engineers will ignore opportunities to improve quality and speed things up. Improvements can be as elementary as using a single screw size throughout the chassis of a processor – the IBM 9370 uses only one screw size. Alternatively, improvements may be very complex indeed.

When I was at IBM, one of the company's most notable turnarounds pivoted on the Proprinter, a dot-matrix printer to be used with the IBM PC. That the Proprinter came out of nowhere to gain a dominant share of the market is well known by now. What is less well understood is how much of its quick triumph resulted from IBM's attention to design for manufacture.

A product well designed for automated assembly becomes less expensive to assemble by hand.

The company was hardly the industry leader in personal printers at the time. When it announced its original PC in 1983, the least expensive model IBM built cost some $5,500 – more than twice the cost of the PC itself, and the company had little choice but to supply a Japanese-made printer along with the IBM computer. So the company mustered a small technical team – designers, manufacturing engineers, and automation specialists – in Charlotte, North Carolina, knowing full well that the luxury of a traditional multiyear cycle was out of the question.

IBM urged team members to work together, not sequentially. It gave them a mandate to simplify the product – and share the same coffee machine. One of the first things they discovered was that the typical PC-attachable printer contained about 150 parts. This was too many parts, and it was an invitation to wasted motion: the more parts you had, the more you had to design, purchase, account for, and store.

Team members determined to reduce that number to only 60 parts, some of these performing multiple functions. In one case, 20 parts were found to be replaceable by one molded-plastic frame. Manufacturing engineers discerned that they could substantially lower assembly costs by designing the product in layers so that robots could put components together from the bottom up. They saw that parts should be self-aligning so that jigs would be minimal. They eliminated all screws, springs, pulleys, and other items requiring human adjustment. Finally, they decided to use molded plastics wherever possible so they could design parts to clip together without fasteners.

Remarkably, the Proprinter came out essentially as planned. It was made from only 62 parts. It printed faster and had more features than the competition – and the team developed it in half the usual time. The product was so well designed for automated manufacture that it turned out to be extremely easy and inexpensive to assemble by hand – so easy, in fact, that IBM eventually shifted a good deal of Proprinter production from the automated plant in Charlotte to a manual plant in Lexington, Kentucky.

An additional benefit was that the Proprinter proved unusually reliable in the field. Fewer parts meant fewer assembly errors, fewer adjustments, and fewer opportunities for things to go wrong later. No screws will loosen in the customer's office if there are no screws in the product.

Five months after launch, the Proprinter became the best-selling PC printer in the industry. Now, just five years after launch, the future of dot-matrix printing is itself in doubt.

Keeping Engineers Up-to-Date

I noted how difficult it is, especially as product cycles shorten, for new ideas or new technology to enter the product cycle from the outside – and for good reasons, not just psychological ones. A lack of familiarity with a particular technology or exposure to it at the wrong time in the product cycle would strain resources and schedules. Only the engineers themselves can deal with these difficulties. They are the only ones who know in detail exactly when they can accept new ideas and what technologies require the tools they don't have.

Engineers need to go out and find what they *can* use and "pull" it into the company. This works far better than anyone trying to "push" ideas from the outside that really may not fit.

Management must encourage engineers to keep up-to-date and know what is going on in the outside world so that when the time is right engineers can pull new technology rather than oppose the unfamiliar being pushed at them. The prerequisite for keeping up-to-date is attending engineering conferences, reading the technical literature, and participating actively in the engineering community. Management must fund these activities rather than regard them as sops to engineers' professional ambitions and cut them at each budget crisis.

Many Japanese companies encourage their engineers not only to attend conferences but to present papers too. This may sound time-consuming; of course it is. But presentations force research scientists and engineers to stand up before their peers, to keep up with the relevant literature and anticipate questions and objections.

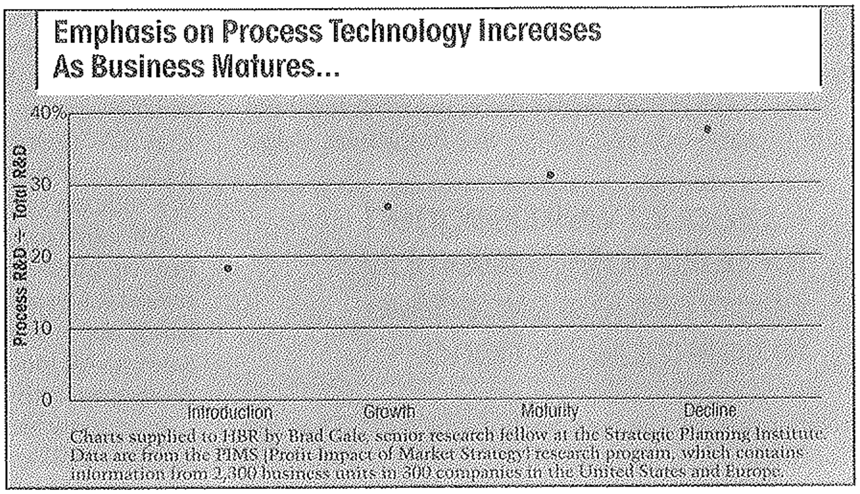
Companies can certainly facilitate communication among professionals in the research organization, regardless of distance. IBM's internal electronic network, VNET, allows company engineers and scientists to exchange message and data files, engage in computer conferencing, draw from among the many databases at the IBM Technical Information Retrieval Center, and search the catalog of IBM's technical libraries. In addition, VNET is a gateway to such academic research networks as BITNET and CSNET, which permit exchanges with university researchers.

Another way for companies to foster technical dialogue is through funding research programs with universities on problems of common interest. IBM has over $100 million in contractual agreements with universities around the world. Although some of the projects are substantial in scope, most are small, engaging only a few researchers. Where possible, IBM lends its own researchers to joint studies and experimental partnerships, and it often supplies extra funding or needed equipment. The mutual stimulation and professional relations fostered by such partnerships can outlast what is learned on a project.

The Sources of New Technology

Any company's relationship with universities, no matter how science-based, has limits. University presidents I've talked with agree that the proper work of universities (and national laboratories) is the ladder of science, not the product cycle – and they are right. They have a superb record in getting basic science done, and they cultivate the intellectual freedom that is far removed from the staggered starts and finishes of product development.

Even when they want to, university researchers can't be much help to companies struggling with their product cycles. How could university specialists in metallurgy know that IBM components engineers working in Fishkill, New York really need to learn more about how solder balls age? Impossible. University people shouldn't be expected to push their findings into the product cycle. It is the responsibility of the company to pull knowledge into the process when it is needed.


Emphasis on Process Technology Increases As Business Matures...

Charts supplied to HBR by Brad Gale, senior research fellow at the Strategic Planning Institute. Data are from the PIMS (Profit Impact of Market Strategy) research program, which contains information from 2,300 business units in 300 companies in the United States and Europe.

Japanese companies have learned to pull research effectively. They routinely send their best engineers and scientists to the graduate programs of our best universities and research institutes not only to study high science but also to get a clear idea of what academic research is being conducted by whom. They scout for science. U.S. companies should be doing the same, even if it means sparing leading design personnel for a year or more.

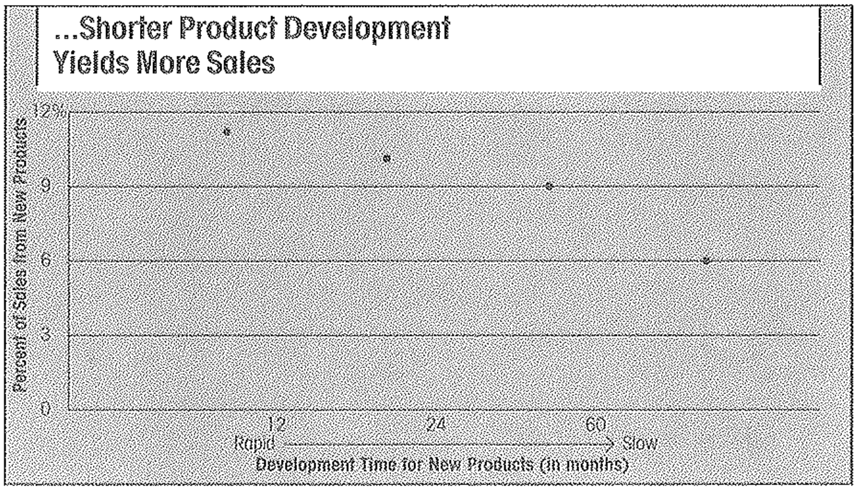
Compared to universities, an in-house industrial-research organization is naturally in a much better position to serve as an engine for cyclic development. A corporate research laboratory's greater technical depth, scientific knowledge, and ties with universities, however attenuated, can directly assist its business units. It is not enough, however, to put the lab up on a hill and hope that ideas will just trickle down to products.

To succeed, the corporate research organization must accept primary responsibility for technology transfer to its business units. And it may be time to start experimenting with new ways of funding corporate R&D. Some corporations – like Philips Industries, N.V. and General Electric – are experimenting with new strictures on their corporate labs that require them to gain a portion of their support directly from the various business units. The theory is that research and development people would more likely work on viable, commercial projects if their research depended on the people who would actually be applying it.

IBM has had considerable success since 1981 setting up joint programs between its research division and various product development laboratories. There are now 19 such programs in areas as diverse as advanced silicon technology to software technology and workstation systems. From the start, such programs were governed by agreements on technical road maps, division of labor, and migration of responsibility. The corporate research division has also worked directly with various manufacturing plants.

Technique and Common Sense

There are technique-oriented ways to shorten product cycles, among them wider use of computerized simulation, which allow manufacturers to avoid much of the cost and time needed to build actual hardware models and prototypes. IBM uses a highly parallel, special-purpose supercomputer called EVE (Engineering Verification Engine) – which simulates the performance of even very large-scale processors before they are built – to toy with different system configurations or spot and correct systems errors.


...Shorter Product Development Yields More Sales

Of course, every manufacturing business cannot build an EVE. But businesses can do some very nice simulations on a PC. Today's enhanced PS/2 or Macintosh II is nearly as powerful as the Cray supercomputer of just ten years ago.

Yet high-tech simulations should not obscure how shortening product cycles is mostly a matter of managerial common sense. For example, management checks and hurdles should help the product development team make a clear business case, or clear up any ambiguities about what the product is trying to be – the market it is directed to, the options it would offer, and the technology that would produce it. Once the project is launched, however, there can be such a thing as too much review, with attendent changes and loss of time.

IBM used to have many hurdles at nearly every step of the process, which encumbered the product team with paperwork and unnecessary fussing. Now the company has only four or five, all at the beginning.

Finally, products should be developed around standard modules, such as keyboards, power supplies, monitors, and standard electronic components. By combining standard modules with more proprietary building blocks – usually sophisticated, specialized electronics and circuit boards – companies can develop the unique characteristics of each of their new models very quickly. One group at IBM, working on a new series of display terminals, trimmed five months off the previous development cycle for the same line of products – just by using standard components.

As citizens, we debate reforms in our schools, military, and budget – changes that will influence our competitiveness ten years down the line. But managers must make changes sooner than that. If our leading high-technology companies do not perform consistently well in the short run, nothing the government eventually does will save the industry from decline. By itself, our population of brilliant, independent scientists will certainly not guarantee a relatively high standard of living. The leads those scientists generate are easily dissipated. Increasingly, our science is a storehouse of ideas that benefits the world nearly as much as it does us.

Yet there is no reason to lose heart. The course is clear enough. We can solve our problems, and cultural change is not a prerequisite. We need to execute elementary, practical reforms that are waiting to be instituted right outside our offices. Speed up the product cycle, encourage close ties between development and manufacturing people, keep engineers up-to-date – there is nothing here that U.S. industry cannot try today.

The United States has managed to be successful on the ladder of innovation. We simply must learn to be equally adept at managing the product cycle. Fix the product and fix the factory. *Then* think about fixing the country. ⛉

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