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The Technology-Product Relationship: Early and Late Stages

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This paper will examine, and distinguish between, two kinds of relationship between technology and product: One which is characteristic of the early stages of an industry and one which is characteristic of later stages. The first one is more or less familiar; and it is the one that has shaped most people's thinking on the subject of science, technology, and product. The second is less familiar. My terminology for these, which you will find in other articles of mine, are the "ladder" and the "cycle."

First of all, let me discuss the more familiar relation of science, technology and product. This is the one that relates to why people came to believe that scientific supremacy should mean supremacy in product markets. This first type of relationship is exemplified by the transistor. The transistor was the product of decades of fundamental scientific research which eventually reached a point of practicality and then, through a series of rapid developments, resulted in the first semiconductor chips and went on to be the start of an enormous industry. And it is that paradigm which is the more familiar one to most people who discuss this subject. This I call the ladder paradigm because the new thing descends from the realm of science—step by step—into practice and becomes the genesis of an industry. Molecular biology is, today, in that state, having emerged from a period of tremendous scientific progress, and is starting to generate a whole new industry.

The belief that this kind of scientific dominance should translate into product dominance is probably, in many cases, the residue of the Second

World War. Those of us who can remember that with any clarity remember the enormous impression made by the science-led, science-developed process of the atomic bomb. And, after the war, we emerged with a picture that scientific dominance does translate into economic dominance. The processes of which that is an example—the atom bomb, the transistor, molecular biology—are scientist-led. Scientists play the dominant role both in the basic research and in the early phases of the industry because they are the only people who understand what's going on in enough detail. So, in the early stages of a new industry, the ladder paradigm predominates. Everything revolves around the new technology. There are no old plants to accommodate; there are new people, new ideas, and new facilities—you are writing on a blank slate. That this kind of activity should produce industrial dominance is an attractive idea. But we should have known better, because the United States, before the Second World War, was already the dominant industrial power of the world, and had been for several decades. And it was not this kind of breakthrough on which that dominance was built, but much more on the manufacturing skills and so forth which are characteristic of the second type of innovation, which I will describe.

Secondly, we should realize that our problems today are not caused by the lack of this "ladder" type of innovation because those industries which cause the negative balance of payments—semiconductor memories, consumer electronics such as TVs and VCRs, and the automobile industry—were not industries that someone else started by stunning innovations. They were industries which U.S. people started and reduced to practice, led and dominated. And it was only in the later stages of these industries that we lost control of them. So, the familiar paradigm is really a paradigm for getting things started. But it is not a paradigm for winning the longer race.

Let me turn then to a second paradigm, a second relationship of technology and science, which I call "the cyclic process." The cyclic development process is a process of repeated, continuous, incremental improvement. It's a problem of getting out a better semiconductor chip next year, based on what you already have in production; or, you are already in production with automobiles, and you are working on next year's model. It is that process of following up what you have in manufacturing with the next model, which is designed, built and prototyped, tested, redesigned for manufacturing, put into manufacturing, and then you turn around and start on the next generation. This process is characteristic of the later (not the earlier) states of an industry.

The type of industry that I am talking about is discrete manufacturing, of which automobiles and transistors are very good examples. It is this cyclic development process that determines in the long run, then, who will be dominant in this industry. It is not as glamorous as the breakthrough type of thing; but, nevertheless, the progress which it brings about is enormous. By and large, the small, innovative companies tend to be very early phases—not necessarily of an industry, but of an industry sector, or of something new. Whenever that settles down and becomes major, then it turns into the cyclic development process. And I think that one way to characterize the difficulties of the American semiconductor industry, perhaps a superficial way, but with a grain of truth, is that it consists of the companies that started it. And those companies have the characteristics that enabled them to succeed in the ladder phase, but they do not necessarily have the scale or other characteristics that would enable them to succeed in the cyclic development process.

Certainly, firms do make a transition from being small startup firms to becoming large ones. But, it is notorious that many of the firms do not; that they have the wrong management style or whatever. Now, I think to succeed today in the DRAM business requires the ability to make enormous investments in plant and in tooling, and to make those steadily because the competition will make them steadily; which means to make them in bad times as well as in good. Now, how would you develop such a capability? I am not quite sure. I think Texas Instruments, for example, has reached the scale where they seem to be able to do that. So, scale is, clearly, one indicator. The second might be to be a vertically integrated company and be a part, say, of a company that makes things that depend on semiconductors. And that when the semiconductor cycle is down, the rest of the thing may still be up. And that might give you the stability needed to make those continuing investments. But you have got to change gears from the rapid one-pass motion of the early stages, to the ability to invest, sustain, and rapidly turn over the crank. That does happen, but a lot of firms fall by the wayside.

For example, in semiconductor chips, by the process of cyclic development, they have gone from sixteen bits on a chip to one or four million bits on a chip, in some twenty years. All of this by the straightforward process of turning the crank: refinement, manufacturing, refine, manufacture. This process is the one which is not clearly visible in most people's minds, and which I want to describe in a little more detail.

First of all, the length of the cycle itself—the cycle from design to manufacture—is a very important parameter and is often mistaken for technological innovation or technological leadership. But consider, if you have one company that can bring a product from design to manufacture in three and a half years and another company that can do it in two and a half years—and suppose they both came out in 1989—the technical notions embedded in the product with the shorter cycle will be one year more advanced. This is simply because, even if both companies are using the same set of ideas, the product with the shorter cycle will embody a later technology. And it will be technically more advanced, though no invention at all has taken place and both companies are simply using the common stream of ideas.

Thus, it is difficult to overestimate the importance of getting through each turn of the cycle more quickly than a competitor. It requires 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 is possible to overtake the industry leader if it has the capacity to turn out a new line six to twelve months more quickly. In fact, our Japanese competitors believe that, in the shortest of long runs, quick development triumphs over market research every time. I once made the mistake of asking a Japanese colleague, my counterpart at that time in an electronics company, whether he had undertaken any research on 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 eighteen months? Why not simply adapt to actual buying patterns? (Why, he implied, should I be bothering with such questions in the first place?)

My conclusion is that a company that can establish and maintain a shorter cycle can develop a decisive advantage over its competitors. The speed with which the design is translated into manufacture, turned around and redone, is enormously important in determining commercial success.

I have taken the case in which technology is changing and, therefore, there is something new to be exploited a year or so later. If market is the issue, of course, the short cycle also gives you quicker ability to adjust to market feedback. This kind of cyclic process is very different from the ladder process. It is not scientist-based. It is based on what is already there, the existing product and its restrictions. If you made a printer last year, and you want to put a new head in the next round of cycle, it has to fit into that printer. If you want to put a better metallurgy in the next round, it has to be one that the development team can deal with, and accept, and get done quickly. If there are only eighteen months for development, there is not necessarily time to do something over from the beginning. So this type of development is very much restrained, not by a totally new idea, but rather by what is already there, whether that is the plant, or the tools, or the engineering team, or what they understand. And if new technologies are going to be part of this, they must fit into that very special world.

If the engineers are partway through the cycle, that is, if they started eight months ago to design the next round of printers, and you approach them with a new head design, you will find that they are not interested. A typical reaction to that is to decry the development people as having the not-invented-here syndrome, to conclude that the company engineers are simply impervious to ideas from outside sources. But this is an inappropriate psychological phrase to describe a genuine, objective difficulty. The resistance of designers to new ideas cannot simply be ascribed to a certain mental inertia—an inertia that accounts for the resistance of U.S. car designers to disc brakes, radial tires, and computer-governed electronic fuel-injection systems or that accounts for how long it took consumer electronics companies to replace metal parts and casings with molded plastics. All this reflects a lack of perception of what the real problem is. To revert to the case of the new printer, the real problem is that, if the engineers are going to bring the new printer out on time, and they are already eight months down the pipeline, they cannot accept a new head. Thus, if you want to get new technology into the cyclic development process, you have a genuine problem: the new technology has to arrive very close to the beginning of the next cycle.

Further, new ideas from any source need to be very thoroughly fleshed out. Many things are hard to accept into this process because the process is bound by the necessities of schedule. It is simplistic to ignore the scheduling compulsions of the cyclic development process and to conclude that what is at issue can be reduced to resistance to outside ideas. If people are building something as part of a development and manufacturing team, what they can accept depends a great deal on what they presently have. It depends on what tools they have, whether they accept square shapes or round, whether their engineers are familiar enough with any particular approach being proposed.

A related point is that it is often also quite difficult for ideas originating in the university community to be quickly accepted into this rather closed world of industry. You can have a great idea at the university, and you can then go to the product developers and say: "Look, I can make a better valve." But even if it is a better valve, the odds are overwhelming that they cannot accept it. Putting a better valve into their equipment may mean that they have got to change 43 tools, and they may quite possibly conclude that is not worth that much disruption.

On the other hand, if the people in industry are familiar with ongoing advances in science and technology, they can go out and pick the ones that they can accept—the ones that fit. That is the phenomenon of "pull." By contrast, it is very important not to assign to universities the responsibility for "push"—for transferring ideas into industry. I do not think they can do it (I am distinguishing here between the "ladder" stages, when universities do indeed play a major role, and the later "cyclical," or product improvement stages, which is the context of the present discussion).

In this respect, one of Japan's great advantages is that much of its technical strength is in entities that are tied to industry or actually in industry, whereas America's scientific strength is heavily concentrated in the universities. As a result, even though Japan's universities have a weak research capability compared to those of the United States, and do not help as much in the idea-generation process, Japan's industries function extremely well in the process of appropriating new ideas.

The essential point is that the primary way that ideas enter the product development cycle is not outside push, but inside pull. The engineers, who are themselves the prime movers in this, go out and select from the great world of outside ideas which are visible to them at engineering society meetings or at universities, those few which fit into their constraints. If you are the owner of a new, technical idea and you go to them, the odds are overwhelming that it will not fit. Your notion will call for stamping something round, but their stamps will stamp square things; and both the time and the cost of changeover make your idea unacceptable.

So, in the cyclic development process, which is the main process of a developed industry, not at startup phase, the key pullers of technological process have to be the people there, not the people outside. This is very different from the ladder process, the early-stage process. Again, because of the importance of cyclic development time, the close cooperation between the design and manufacturing is absolutely essential.

Of course, the manufacturing skill, itself, is a tremendous factor, as are the closely related issues of quality, but I don't propose to get into that issue here because they have been exhaustively described by many other people.

I just want to mention, though, the importance in a short cycle of designing for manufacture, on the part of the design team; and I will illustrate that by an example which perhaps you have heard of, but perhaps not in as much detail. And that is the example of the IBM ProPrinter.

The IBM ProPrinter was a matrix printer, exactly the sort of a thing you would put on a table next to your personal computer. It hammers out letters by driving little wires into a ribbon, the choice of wires determining the letter that emerges. It is basically a mechanical device. IBM was not originally competitive in the production of these printers. And when the early PCs, the first PCs, came out, they were all equipped with competitors' printers—notably Epson printers. And when IBM's development team looked into how it might have a competitive machine, one thing that was immediately discovered was that the IBM designs had many more parts than the competitive designs. The number of parts in the IBM design was, I think, roughly 120 or so in the Epson-type designs. For the first time, the development team took very seriously the consequences of designing things that way. They concentrated on designing the next printer as a manufacturable printer. And they took as their goal 60 parts. The number of parts is not a bad surrogate for the complexity of assembly.

There also was a second theme, which was pure manufacturing. They put together a robotic line. They cleaned out an old plant and put in 35 robots, two-armed, highly programmable robots to assemble this thing—and spent a lot of money doing that. I, myself, was very pleased to see the two-arm robots go in there because they were the product of a project which I had started in IBM Research in 1972. So, I thought this would be very spectacular. Here is what happened.

The design goal was almost met. They emerged with 62 parts. They designed the machine to make it easy for the robots to put it together; and that meant that the parts were all put down top-to-bottom, no insertion sideways. There was also a rule—no screws and no springs—because screws and springs are also hard for a robot to assemble. They made it with 62 parts, no screws, and no springs. Now, when they assembled this printer, they found that a human being could assemble this in roughly three to four minutes. It was that easy to put together because it had been designed to be manufacturable.

Another thing that occurred, by the way, was that the development time was cut approximately in half from previous development times. So, they affected the development cycle by making it simple, and they made it so easy to manufacture that, in fact, the gain due to the investment in the robots was almost completely obviated. Because if the human being could put it together in three and a half minutes, a very expensive robot had a real problem in just funding itself.

I have difficulty separating the managerial issues of this process from the structure. Is it structure that makes you turn the cycle fast—or other things—or is it management? I do not know. The point is, one way or another, you do it. Now, in the case of the ProPrinter, someone, I do not know whether it was management or other people, took the competing thing apart, and found a very small number of parts. And someone had the wit to say, "Let's have less." Now that may seem very trivial, but it is a change, or change of view. It is a change to say, "Our job, as engineers, is to make this thing manufacturable." I don't know whether that is management or organization. I am really describing what has to be done. I think, in some cases, it may be a spectacular individual that does that. And, sometimes, it will simply be the sharp spur of necessity, knowing that the other guy is going to bring out the next round two years from today and you'd better have something there. And there may be no spectacular individual at all involved. Perhaps the "Champion" concept matters less in the world of cyclic development. I think the system itself can drive it, if you know where you are going wrong.

I bring all this out to emphasize the importance of the cycle and of design for manufacturing. This printer went on to become the best-selling printer of that type in the United States. This was not due to a scientific breakthrough. It was due to proper design for manufacturing. By the way, that is a learnable thing; and, when people talk, as they often do, about the difficulties of competing with the Japanese because of various and mystical factors, that we must change the entire U.S. culture in order to compete, we have got to redo the educational system, etc.—let me point out that competitiveness was achieved, in this instance, by changing the culture, not of a country, but of 70 people; the 70 people who made up that design team. So, there is a great deal of competitiveness that is concrete, focusing on the manufacturing/development cycle, on finding ways to shorten it, on finding ways to design for manufacturing, and finding ways for the engineering team to pull ideas into the next product.

And let me say once more that, in the taxonomy that I use, this cyclic development process is, in the long run, the decisive one for many manufacturing industries.

Now, if we do look at the competition—at the Japanese competition—we find that they do all the things I am talking about. They do design for manufacturability extremely well. In fact, the design and manufacturing teams are often very much tied together. They do have very short cycle times. If you read the press, you would think that the

Japanese owe a great deal of their success to the very advanced technology programs which MITI has sponsored. Now those programs are useful, but they relate to the early stages of technology, not to the rapid turnover of the cyclic development process. And in the areas which I have seen, and with the people with whom I have discussed these matters, it is the cycle, not the ladder, that has been decisive in the industries in which we are in trouble—automobiles, semiconductors, TV; that sort of thing.

Another striking contrast with the Japanese is relevant here. In most American firms the people who are responsible for development, and those who are responsible for manufacturing, tend to live in different worlds. In U.S. industry, the high prestige is in development. The manufacturing task is considered to be relatively dull, repetitive, and for the uneducated. Therefore, production considerations have not been an early part of the design, say, of a new car or computer or printer. Until very recently, the product was not designed to be manufactured. It was designed to work, to make good print, or to run fast, but it was not designed to be manufactured. When the prototype was ready, you simply handed it to a different group of people—the manufacturing people—and you said, "Okay, I made one, you make 10,000."

In Japan, curiously enough, it is the other way around: Manufacturing calls the shots. Manufacturing people are highly trained, but people also move back and forth a good deal between various functions. The distinction we tend to make between the engineers in development and those who replicate their designs does not exist in Japan.

So, let me sum up what I am saying here. Much of our thinking about innovation comes from the ladder process because it has been so visible and so spectacular, involving the emergence of a new scientific effort and new products emerging from that effort for the first time. The United States has, in fact, historically been very good at that, while it has been steadily losing in the cyclic development process which is the phase characteristic of the mature industry. Now, that does not mean that we should let go of the first process because you can lose at that, too, and the Japanese are making much more of an effort in those early phases than they did in years past. But it does mean that we also have to make the cyclic development process more visible and to understand it better.

I believe strongly that the invisibility of that process does hurt us. Many of the words that we use to describe this subject hide, by their very meaning, the fact that there is a cyclic development process.

I think the wrong mental picture hurts us a great deal. Let me be concrete. Consider the picture brought to mind by the phrase, "commercialization of new technology." If you talk to most people, I think you will find there is a notion that commercialization means to take something new and make it commercial, whereas the essence of the cyclic development process is you are refining something which is already commercial. When you talk about the commercialization of scientific discovery, those words already specialize you to phase one, or the ladder process.

The United States, as a whole, seems to resonate far more to the spectacular events of ladder innovation. Take, for example, superconductivity—high-temperature superconductivity. High-temperature superconductivity, from the point of view of industrial competitiveness, is something that is way, way out there—at least, optimistically, ten years away, if ever. And yet, when that great scientific event occurred, we had meetings in Washington, with the President of the United States in attendance, special legislation in Congress, set up special committees to advise the government, etc. A tremendous focus on a ladder-type event and, in all the discussion about it, the close tie with industrial supremacy which, in fact, does not exist.

It is necessary, therefore, for us to learn the ins and outs of the cyclic process, because, very often, that is the decisive process. And, if you look at that picture, I think you will find that it does turn around what you have to think about.

Take, for example, the notion of investing in R&D. A lot of people, if you are talking to them, will say, "Gee, the Japanese are investing a lot in R&D and that means they are going to jump past us," or something like that. And, again, the picture is, you put the R&D in here and the product pops out. That is very, very different from the one you really encounter if you are a participant in a cyclic development process, because in the cyclic development process it runs much more like this. You have a product. The product is selling. That gives you a certain stream of revenue. You can take that stream of revenue and put some of it into R&D for the next round. Some of it has to be reserved for the manufacturing, some of it for profits. Now, if you are on an upward swing and your product is succeeding, you have a flow back of money to invest into R&D; and if it isn't, you don't. And, in my experience, and the experience of many other people, oddly enough, R&D is determined, more or less, as a percent of sales. It is not an independent variable.

Let me say that once more. R&D is often a fixed percent of sales. Now I exaggerate to make the point. Ten percent is a very reasonable sort of number in a high-tech industry. Now, there may be some nonlinearity in relation with production. But, as you produce more, you spend more on R&D. It is not at all clear that in this phase of the industry, the cyclic development phase, that the R&D decision is an independent decision. As it is often discussed, "We have decided to invest in R&D" is a phrase that fits, again, much better at the front end of an industry. Later, what you can afford is determined by your success in the cyclic process. And it may be that, in the correlation, which has often been remarked on, between R&D spending and industrial success, it is the industrial success which causes the R&D spending, not the other way around.

I think that high-definition TV is just one more step along the continuum of TV products, but it is being represented as something totally new, and a tremendous opening to go in. I think that it would not be very different to decide that you want to get back into TV. I think getting into HD-TV is not that different a decision; and the only way to do it would not be the sort of things that were originally happening—which is, "Let's have DARPA spend some money in R&D." This is a total misconception related to mistaking the ladder for the cycle. You are still in a cycle process, in my opinion. The only way that you can enter HD-TV is to build up a manufacturing capability, on a very large scale, and back it up with a major R&D, and start the cycle churning. It is not that kind of an event where you can come in from the outside with a new technology. It is a cycle event, not a ladder event.

So, I think we need to rework our mental picture if we are to make progress with this matter. And in the subject of cycle versus ladder, and the characteristics of the cycle, there is much to learn. Of course, the ladder process is not always quite as separate from the cyclical process as I depict. A good company is continually investing in both kinds of developments and the problems within both of them. It is how to move things along that is the problem. But if we do not realize that there is a cyclic development process with its own peculiar resistances, then things will not move. Believe me, I had a very expensive and extensive education along those lines. So, I do very much believe in doing the research. But you then have to pay attention to how it will get into product. Much research is done, and it never will get in, because it will violate the rules. It will deal with an object that is not there. It will not understand that there is an issue of timing, that there is an issue of familiarity, and so forth. You have to understand that this cyclic beast is grinding away, and this is the beast you have to affect, and that your invention is only a part, and you have to match the timing and you have to match what is there. And, otherwise, it just does not happen. It is not enough to have done it. To have done it is to put it on a shelf, along with many other inventions or innovations; and then, various companies will come along and pull from that shelf the thing that fits their cycle. Now, which company does that—who knows? I think it is very wise for companies to be assiduous in that process. If you are talking about things that a company itself develops, then it had better pay attention to what is known as technology transfer, a very nontrivial process, because the thing you are transferring to has its own life structure.

Let me close with an important caveat with regard to the transfer of technology. Success or failure in technology transfer depends critically on the characteristics of the receptor. If the receptor knows very little, he can do very little even with a simple idea, because he cannot generate the mass of detail that is typically required to put a new technology into execution. On the other hand, if he knows a great deal and is capable of generating the necessary details, then from just a few sentences or pieces of technology he will be capable of filling in all the rest. That is why it is hard to transfer technology to the Third World and very hard not to transfer it to Japan.