Technology Development

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Summary. In technology development significant advances are as often the result of a series of evolutionary steps as they are of breakthroughs. This is illustrated by the examples of the steam engine and the computer. Breakthroughs, such as the transistor, are relatively rare, and are often the result of the introduction of new knowledge coming from a quite different area. Technology development is often difficult to predict because of its complexity; practical considerations may far outweigh apparent scientific advantages, and cultural factors enter in at many levels. In a large technological organization problems exist in bringing scientific knowledge to bear on development, but much can be done to obviate these difficulties.

Basic scientific research, with its tradition of open communications in an academic, or academic-like, setting, is widely described and commented on in the public press. Many college graduates have some idea of how scientific research is conducted by having seen at work the professors who are the backbone of the scientific professions. The history of science and, more recently, even the sociology of science are established fields of scholarship.

Technology development, on the other hand, occurs mostly in industrial settings, and many fewer people get to see it. It is usually not well described in the public press or in the history that people learn. It is therefore not surprising that the evolution of technology development is often confused with science in the public mind.

Yet this poorly understood, invisible process of technology development is what we all depend on for improvements in our material daily life, for the transmission to other countries of knowledge that we hope will raise their standards of living, and, to a considerable extent, for our own country's strength and progress.

Technological Evolution and Breakthroughs

Technology development is much more evolutionary and much less revolutionary or breakthrough-oriented than most people imagine. It is important to realize that a series of evolutionary steps in technology, together amounting to a large improvement, is just as revolutionary as a breakthrough. That this is the normal course of technology development may be illustrated by two historical examples. These examples are given here not only to illustrate this abstract point but to furnish concrete instances as a basis for a real understanding of technology development.

Steam Engine

The first is the steam engine. The popular notion of the development of the steam engine includes the story of how James Watt was in his mother's kitchen, the kettle boiled, steam came out, and Watt realized the tremendous power of steam and later invented the steam engine. This story has nothing to do with reality, and Watt had nothing to do with kettles. The true origin of the steam engine is very different and much more interesting.

The history of the steam engine may be considered to start in about 1680 with the famous Dutch physicist Christian Huygens, who was trying to develop an engine based on gunpowder. It was recognized at that time that there was power in gunpowder or in fire which, if it could be harnessed, would furnish another source of energy. This could then supplement existing energy sources of the time, which were animal power (for example, horses turning treadmills), wind power (windmills), and water power.

Huygens did not attempt to harness the explosion of gunpowder directly; his method, which was more sophisticated than that, was to explode a little gunpowder in a cylinder, under a piston. The piston was already up, and the idea was that the explosion would create a vacuum and the weight of the atmosphere would then push down the piston. Although it was a rather sophisticated approach it did not work, because the explosion left behind residues and did not create a sufficient vacuum.

However, Denis Papin, an assistant of Huygens, conceived of a way to use steam to create a vacuum. His idea was to boil water over a fire (thus capturing something from fire), put the steam in under the piston, close the bottom of the container, and let the steam cool so that it would condense. This would create a vacuum and down would come the piston. In about 1690 Papin built a model, a small-scale engine of this type, and it worked.

In England, about 8 years later, Thomas Savery made the first full-scale working steam engine. He had a number of problems with it. Savery did not use atmospheric pressure. He used steam to drive the piston, and he used it at high pressure. Unfortunately, the mechanical technology of that time was not up to full use of the design. The machine worked but had troubles with high-pressure steam, and its use was restricted by the pressures that the boilers and piping could withstand. It was used mainly for low water lifts to pump water for waterwheels and supply water to large buildings. But this design fell into disuse.

The next step was due to Thomas Newcomen, a plumber. Indeed, one of the morals of this history is that the people who did this work were plumbers, wheelwrights, and instrument makers. Newcomen came up with the first reliable and widely used steam engine. It was basically a blown-up version of the Papin engine. Water was boiled in a boiler and the steam was put into a cylinder. A spray of cold water was applied to the cylinder to cool the steam and create a vacuum, which in turn forced down the cylinder. Then the piston was lifted back up, and the cycle was repeated. The Newcomen engine became important in early 18th-century England, where it was used largely for pumping water out of coal mines. This was an important application: many coal mines were unusable unless they were pumped out all the time. In fact, many mines were abandoned because people could not keep the water out. It was a life-and-death problem for the coal min-

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ers. The Newcomen engine found a niche where it could survive, and for 20 or 30 years the technology consisted mainly of Newcomen engines pumping water out of coal mines—until it took the next step forward.

Before describing the next step and its effect, a number should be introduced: the "duty," a measure of the goodness and efficiency of engines. This was the number of millions of foot-pounds of work an engine could do by burning one bushel of coal. The duty of the Newcomen engine was about 4. A rough estimate of the work a horse could do for the same cost falls somewhere between 14 and 24.

The next step was taken by John Smeaton, who, around 1767, made a better engine and raised the duty to 7 to 12. Invention, it should be stressed, did not play a major role in this improvement: Smeaton knew how to bore cylinders better. The best mechanics of that time could bore a cylinder for a steam engine only so accurately that one could insert a worn sixpence between the piston and the cylinder. This was why they used the atmospheric engine rather than high-pressure steam—much less steam escaped.

Finally, around 1775, James Watt appeared. The real Watt was an instrument maker, and he got into steam engines because he was given a small model of a Newcomen engine that did not run and was asked to fix it. While working on the problem he realized that energy was being lost by heating the cylinder with steam and then cooling it to condense the steam. Watt solved the problem by supplying the engine with a separate condenser. The cylinder remained hot; the condenser remained cool. This raised the duty of the engine by about another factor of 2.

Later in his life, Watt introduced a two-stroke engine, with the atmosphere driving the piston one way and steam driving it the other. That was worth about another factor of 1.5. The duty was raised by these innovations to between 24 and 35.

In the period 1800 to 1830, engines with more than one cylinder were introduced, and by that time the mechanical technology permitted the use of high-pressure steam. With these innovations, the duty went up by another factor of 2 or 3, from about 37 to nearly 100. The small technology that for 20 or 30 years existed mainly in the business of pumping out coal mines had been transformed, through a series of evolutionary steps, into the energy source that changed the world.

Two points in this story are characteristic of the development of new technologies. One is the cumulative effect of small steps (note that mythological history has erased that and replaced it with a single breakthrough on the part of James Watt); the second is the significance of the niche (in this case coal mines)—the special place in which a technology may survive, even though it is not yet ahead of other technologies of its time in more general applications.

Computer

The second example I would like to discuss is the computer. As a concept, the computer existed in reasonably well-developed form in the first half of the 19th century. More than 100 years ago, Charles Babbage, a well-known English inventor, conceived the idea of a programmable computer. However, the technology of his time—cogs, wheels, and axles—did not permit the easy realization of such an instrument and there was little demand for computation outside astronomical tables. The beautiful idea that Babbage worked out was not realizable in the circumstances of 100 years ago. It was much later that vacuum tube technology made computers feasible while the impetus for large-scale computing was provided by World War II. The combination of technology and motivation gave rise to the first generation of vacuum tube computers: the ENIAC, EDSAS, and EDVAC, the Whirlwind, the Institute for Advanced Study machine, and many others. There was an early period in which many technologies competed for the role of memory—for example, storage tubes, cores, and thin-film memories. Finally, the transistor, invented at Bell Laboratories, came along and swept the whole development into a totally new phase.

The transistor was a real breakthrough. It was the result of a long buildup of understanding of solid-state physics and then a rather sudden transfer of that knowledge into a new area—the area previously populated by vacuum tubes. Once it got going, this development, like the steam engine, was in the hands of practitioners. It was mentioned before that the evolution of the steam engine was conducted by mechanics, plumbers, and so on. Similarly, the transistor came out of fundamental scientific knowledge, but its continued development was in the hands of semiconductor engineers, where today it is evolving rapidly. In 1968 memory chips held 16 bits, 4 years later 1,000, and today 64,000 to 128,000. There is every reason to expect 256,000 bits per chip in the next few years, and so on into the indefinite future.

The evolution of the transistor has also spawned the microprocessor, which is often described as a breakthrough, but which can be regarded as such only in the sense of an application breakthrough. The development of the microprocessor was foreseeable. Every year more and more circuitry could be put on a chip. Looking a few years ahead, one could realize that an entire processor, or the central processing part of a computer, could be put onto one chip. Finally it happened, and when it did there was an enormous number of applications for it. That was the main element of surprise.

The arrival of the microprocessor was unavoidable, given the rapid evolutionary progress of transistor technology. I am stressing the evolutionary part, and that is the state that computer technology is in today. I think that the computer is the analogy in our time of the steam engine, in its technical evolution and in its revolutionary impact. If I seem to be down on breakthroughs, it is because I think they are both rare and extremely important. I think we do have them. I do not like to see the confusion that occurs when that name is used for what is just the next step in technology, because it obscures the true nature of much important technical progress that is evolutionary. The transistor itself was a genuine breakthrough. Recombinant DNA and its application to chemical processes are breakthroughs. These are not the next steps in a technology but are the introduction of something quite new.

The transistor was the result of long, patient, and mainly undirected basic scientific work that led to a sufficient understanding of solid-state physics to make it possible. The knowledge that led to its introduction in a field where only vacuum tubes had been before came out of another field. Similarly, the atomic bomb was not the evolutionary outgrowth of explosives but represented the introduction of knowledge about the structure of the nucleus into the field of weaponry. Similarly, recombinant DNA—should it prove to be successful in chemical processing—will be the introduction into a new field of the accumulated knowledge about the fundamentals of molecular biology.

Real breakthroughs do occur; they are rare and stunning events. The more common course of technological evolution is steady, year-to-year improvement, and when that is rapid and persistent, the results are just as revolutionary.

Characteristics of Science and Technology

Armed with these histories of the steam engine and the elements of computer technology, we can raise questions about science and technology. How do they interact? The two examples cited indicate, as many have observed, that it is a two-way street and that science and technology affect each other, and are affected by each other, in more than one way. Of course, we are accustomed to the idea that science contributes to technology. The early history of the transistor is an example of the introduction of scientific knowledge into technology with stunning results. On the other hand, the development of the steam engine was the work of practical men gradually adding improvements driven by the needs of application. This persisted until the 1830's, when the need to make still better steam engines and to understand them stimulated the development of the science of thermodynamics. Technology in that case drove fundamental science. This is happening today; the computer is driving computer science. Furthermore, the evolution of technology makes better scientific instrumentation possible, and this can be a major factor in the advancement of science.

What are some of the characteristics of science and of technology? Science can be thought of as a large pool of knowledge, fed by the steady flow from the tap of basic research. Every now and then the water is dipped out and put to use, but one never knows which part of the water will be needed. This confuses the funding situation for basic science, because usually no specific piece of scientific work can be justified in advance; one cannot know which is going to be decisive. Yet history shows that keeping water flowing into the pool is a very worthwhile enterprise.

Scientific research, which feeds this pool, has its own culture and its own imperatives, which are very different from those of technology. It is motivated by the desire to satisfy curiosity, as opposed to the imperative of technology to get out a working product.

In the United States, science (in contrast to technology) is highly valued. Scientists are esteemed more than the practitioners of technology. Science is primarily university-oriented and to a considerable extent government-funded. The principal citizens of science are Ph.D.'s. It is reasonably represented on the national scene. All but one of the Presidents' science advisers of the past (Frank Press, H. Guyford Stever, Edward E. David, Jr., Donald F. Hornig, George Kistiakowsky, and Jerome B. Wiesner) come from the world of science but represent both science and technology. The current relative prestige of science and technology is peculiarly American. The situation varies a great deal from country to country, and in some countries it is considerably different from that in the United States.

Technology is different. It is manned primarily by engineers, not Ph.D.'s. It is usually industry-oriented rather than university-oriented. It is driven by applications and products rather than by the imperatives of science. However, perhaps the most important point about technology is that it tends to be very complex.

Because of its complexity, developments in technology are sometimes hard to predict. The problems and the advantages of evolving new technologies are often not obvious. In the early days of the transistor, germanium was selected as a transistor material because it allows electrons to move more rapidly than they do in silicon. This seemed to promise much higher speed. But, in fact, it turned out that silicon almost completely supplanted germanium because it naturally grew on its surface a layer of oxide that protected the finished chip. That practical consideration far outweighed the apparent advantage of germanium. Today we have almost entirely silicon technology.

Another example is Josephson technology, a proposed new computer technology, which relies on superconductivity and some variations on it that occur only in certain metals and at temperatures near absolute zero. We understand all these complex phenomena, but they are not the problems with this new technology. The actual problems are more mundane, but much harder and of the following sort.

The computer itself is complicated. Large computers have to be repaired during their lifetime, partly because things break down and partly because they were designed wrong in the first place (no one has yet designed a large computer completely right). In the course of its lifetime, a large computer has to have the capability of being repaired, let us say 300 times. If you were repairing one of the machines that depends on superconductivity, you would have to take the cooled elements out of their cooling bath to fix them 300 times—and that means that all of those elements would have to be able to withstand the expansion of coming up to room temperature and being cooled off again 300 times without anything going wrong.

The phrase "without anything going wrong" masks another level of complexity. The computer might have 7 million basic elements. Those 7 million elements would all have to be warmed to room temperature and cooled again 300 times with a minimum of failures. If one failure occurred every time the computer was warmed, then after cooling the computer would have to be warmed up again right away to repair that one failure, which would probably cause another failure, and the result would be a totally inoperative machine. The difficulties in this technology, therefore, are not really in understanding the difficult phenomena; they are in making very tiny elements that can expand and contract 300 times and in creating an assemblage of 7 million of those elements that will almost never have even one thing go wrong with it.

In addition, a machine like a computer has to be manufacturable, and this introduces a whole new set of extremely difficult requirements before all of the small components will work.

To illustrate the requirements related to manufacturability, I will discuss the magnetic bubble device, in which a small thing called a "bubble" moves from one tiny piece of metal to another. For the device to work, the two pieces of metal have to be the right distance apart, or the bubble will not jump the gap. The bubble has to travel within a layer of material (garnet) that must be the right thickness, and it is moved by a magnetic field that provides a particular force. The practical problem is to manufacture these tiny devices with such precision. The two pieces of metal are never exactly the same distance apart; they may be 10 or 15 percent off. The thickness of the layers may vary by 5 percent; the magnetic field is never completely uniform. The result is that the design must have a tolerance window that will permit the device to work even though the distance is 15 percent off, the thickness is 5 percent off, and the magnetic field may be 8 percent off. In addition, all of these things vary with temperature, so that the design also has to take into account a certain temperature range.

In new technology development, even if you are looking at a working device, you may be looking at something that needs a couple of years of redesign work before it is manufacturable, because it has to be designed so it can withstand all those changes and still work.

Cultural Factors

In dealing with technology, things are sufficiently complex that much is done by rule of thumb and not by precise knowledge. Many factors enter in; some of them are even cultural. (I am using the word culture here only to indicate a general set of habits of a group of people. There is no implication that this culture is unchangeable; in fact, it is very changeable.) Let us consider an example. A complex part was being made. It went through a large number of process steps. Only about 6 percent of the parts that came out at the end worked. That was not nearly enough because, with the cost of the whole process, a 6 percent yield made the parts too expensive. On the other hand, no one could find anything seriously wrong with the process. So the engineers moved in and stood where the production people had been, and they carried out the process in the hope of finding out where it was going wrong. They never found anything wrong with it because they got a yield of approximately 60 percent when they did exactly the same thing. Eventually it became clear that the people who had been doing the processing simply had not been trained to be precise enough. Sometimes they put a screwdriver in a hole that was later used for precise positioning. In handling a part they sometimes made little nicks and scratches on it or touched it with their hands. Later, things would not adhere to the surface that had been touched. The accumulated effect of those things made the difference between 6 and 60 percent.

Technology is culture-dependent in other ways. Cultural factors such as attitudes toward financing (long-term versus short-term goals), attitudes toward carelessness and small mistakes (quality), and the presence or absence of the famous NIH (not invented here) syndrome (it is hard to get someone else's idea into your laboratory) have a tremendous influence on technological progress.

The best example of culture interacting with technology is, of course, Japan. I refer not to modern Japan, but to the Japan that was opened up to the world by Commodore Perry in 1854. The same country, in 1905, using Japanese-constructed battleships and naval guns and a combination of the most complex technological instruments of that period, destroyed the Russian fleet in the battle of Tsushima. This remarkable transformation from a feudal state to one that could create the most technically advanced machines of its time in a span of 50 years is, to my knowledge, unparalleled in the history of technology. That culture has continued, and Japan is once again making tremendous strides. Other countries, for reasons we do not really understand, have had much more trouble assimilating technology. China, for example, which many people consider to have been culturally superior to Japan for thousands of years, has never under any kind of regime been able to make that kind of technological progress. Great Britain, which started and led the industrial revolution, is today strong in science but weak in technology. There is no simple connection between scientific mastery and technological leadership. When the United States and Japan are compared on a scientific level, the United States is well ahead. But on a technological level, it is quite another story.

Technology Transfer

This picture of technology as a complex and even culture-dependent process bears on a number of things, including security, in the sense of secrets, and technology transfer, in the sense of trying to get a technology to someone else in the same country or in other countries.

It is hard to keep a simple idea secret. The idea, for example, of having a separate condenser for a steam engine can be expressed in one sentence. It is hard to keep that one sentence a secret. On the other hand, it is hard to transfer the full complexity of a technology. There is too much. Those who are not technologists in the same field cannot even be sure which details matter. So simple things are hard to keep secret, and complex things like technology are hard to give away.

Let me add a caveat, which is that everything depends on the receptor to whom the secret or the technology is to be given. If the receptor knows very little, he can do very little even with the simple idea, because he cannot generate the mass of detail that is required to put it 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 fill 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.

Technology, more than science, moves forward in a world in which time and expense are extremely important. An experienced colleague of mine, Robert Henle, told me that there is a saying that in technology you never run out of ideas, just out of time. I saw that borne out some time ago when we were trying to get a new printing technology ready. It took longer and longer, and finally we stopped the effort and substituted a conventional technology in order to get the product out. People working on the new technology said that they still had a lot of ideas about how to fix it, and that was true. We had not run out of ideas, but we had run out of time.

New technologies are generally expensive because they are not yet refined. Therefore they often cannot compete with existing, in-place technology, which has been refined. That is where, in the case of the steam engine, the coal mines came in. Often new technologies depend on finding some small use that can keep them in existence while they improve. If they do not find it, they will never reach their full potential, because no one will spend the money to keep them going.

This, incidentally, is an important role that military procurement fulfills, even though it is a small part of the commercial marketplace, because military requirements often place extreme demands on quality and capability that can only be met by new technologies. Those technologies are thus kept going and are given a chance to grow to maturity.

Scientific Knowledge

All kinds of fundamental issues arise in the course of technology development which require the most advanced scientific knowledge or even new scientific knowledge for their solution. The effect of cosmic rays on computer memory is an example. To understand what happens and to prevent loss of information from the memory requires knowledge of the detailed interaction of these particles from outer space with the crystalline matter of the transistors and the ability to trace the effects of this interaction into the memory. So we need directed basic research—that is, work done at the most fundamental level, but intended to get certain practical problems solved. This should not be confused with the important pool-filling activity alluded to earlier.

Organizational Problems

Bringing scientific knowledge to bear on technology is not easy. Inventions or solutions to problems occur when the knowledge of a need and the technical or scientific knowledge to cope with that need finally come together in one head. Everything else is just a means to that end. Those means often become elaborate, except in a very small organization.

Small organizations have their own problems. They usually do not have the technical skill to solve fundamental problems unless they are set up specifically for that purpose. In most large organizations there is an elaborate apparatus that, in one way or another, tries to take knowledge of a need and translate it into a clear-cut technical or scientific problem. The need for more speed in computers in the marketplace may be translated into saying to a person with a knowledge of ceramics, "I need a new ceramic with a lower dielectric constant." This long process of translation usually calls for some organizational apparatus. However, organizations tend to develop a life of their own. The individuals or small groups whose scientific knowledge you rely on and to whom you try to translate your needs may be more interested in ceramic science than they are in computers. The fact that your requirements are written down does not remove the difficulty. Written documents are often worse, because without a dialog between individuals it is difficult to convey exactly what is meant and what is really important. These problems are not easily dealt with. In fact, it is hard to overestimate the diluting and distorting effects of long chains in organizations, long chains of command, or long chains of information transmission.

One way of overcoming these effects is to have people move around. Researchers should know what development is like; developers should know what their product is used for. In that way, these difficulties can be short-circuited to some extent. Another stratagem is now and then to talk to someone at the bottom of the organization and get an exact and detailed account of what he is doing. An executive may think, for example, that his organization is investing in navigation, only to learn that it is investigating turtles laying eggs. That may sound funny, but there is a real connection.

One way to study navigation is to study animals that exhibit remarkable navigational ability. An example is the sea turtle. It is difficult to study sea turtles in the water, so people start by studying sea turtles on the shore when they come out to lay their eggs. That may well be what is going on in the organization, and it may be necessary to decide between producing a new navigational device in a few years or contributing to the basic pool of scientific knowledge, which experience has shown to be useful in the long run.

The usual problems of an organization are made more acute when it is technologically oriented. In an average organization, usually a hierarchical one, there is an implicit assumption that the people with the power to decide, the people in certain positions of the hierarchy, also have the knowledge to decide. In a sales organization, for example, the veteran salesman has first been a sales manager; he knows how to run a branch office, then he runs a group of branch offices, then he runs a region, and so on. He understands reasonably well what it is all about.

In a technological organization, it is often the case that the person with the power to decide does not have the detailed technological information needed to make a decision. These complications can be dealt with. A special task force is often formed at this point. This is an ad hoc group of trusted people with the technical knowledge to investigate the question at the right level of detail and report their reasoning and conclusions to the person in charge.

Morale and attitudes are also important in dealing with this difficulty. Key technical people must feel free to make their views known. The person in charge should also have key technical people, not usually those who report directly to him, whom he feels free to consult. All this is easier in an organization with enthusiasm and a shared sense of purpose and direction.

Conclusion

In this article I have attempted to bring out the evolutionary character and the complexity of much technological development. Technology development is sensitive to detail and to the culture in which it is embedded. It is an activity that is not well understood today, yet we must go forward with it. Much of our individual and national welfare depends on the success we make of it.