CHAPTER EIGHT

Entrepreneurial Creativity

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WORLD ECONOMIC GROWTH, particularly continued U.S. economic growth, depends on founding new markets and new industries. Scientific and technical invention, no matter how brilliant and creative, is only one step in the founding of high-tech industries. Entrepreneurial creativity is also needed.[1] Such creativity is typically linked to scientific and technical advances, and is sometimes displayed by the same people and firms that make key technical advances.[2] In a market economy, however, entrepreneurial creativity is often widely dispersed, and the openness of the market economy is as important to it as the openness of science is to creative outsiders.

Entrepreneurial creativity locates and exploits overlaps between what is technically feasible and what will create value for society.[3] This is the key step in the founding of new technology-based industries, and it is often very difficult. The list of feasible scientific and technical advances is a long one. So, too, is the list of new products, new markets, and new industries that will create value, either by serving existing needs with fewer resources or by generating new ways of making people better off. Economic growth since the first industrial revolution has taken both forms of value creation: the provision of food, clothing, and shelter requires vastly less resources today than it did a few centuries ago; and the invention of new and better goods and services lets us live much better than our ancestors, for whom subsistence and warmth were critical.[4] Finding the overlaps between technical opportunity and value creation is one of the most demanding conceptual tasks in creating technical advances in the modern economy, and it depends critically on entrepreneurial creativity.

Seeing new overlaps is difficult because knowledge is dispersed widely in the economy. The most important economic growth driver of the rich economies in recent years involves the use of computer systems in large organizations, in markets (electronic commerce), and in the creation of online entertainment media such as social networks. Computer systems draw on new science and technology to a great degree, of course. However, understanding computer technology deeply does not endow computer specialists with deep knowledge of markets, entertainment, or the delicate arts of social communication. That knowledge is, typically, held by others. More generally, when markets and industries do not yet exist, there is no good reason for the same person to have knowledge of both technical feasibility and value creation.

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One source of entrepreneurial creativity is individuals who see the overlaps. These people are the most obvious "entrepreneurs" in society, particularly if they found new firms. For modern technical change, however, as we shall see, thinking about only the lone, heroic engineer is an important mistake, and a further mistake to think only about that person's garage. Much entrepreneurial creativity occurs in complex market processes involving a number of creative steps, and some occurs in large, complex organizations too big to fit in a garage. This is not to say that the founding of new firms (even in garages) is unimportant, but rather that it is only one aspect of the creative process that leads to new markets and industries.

Entrepreneurial creativity is related to, but distinct from, scientific or engineering creativity. Indeed, some very important instances of entrepreneurial creativity are dismissed by technologists as uncreative—

"mere marketing." Entrepreneurial creativity lies in seeing the overlaps between technical feasibility and value creation. Entrepreneurial implementation lies in building the firms, markets, or industries that exploit a technological opportunity to create the value. In many ways, this market focus distinguishes entrepreneurial creativity. The new product or process innovation that serves an important need may appear quite mundane, but if it was not foreseen, it is creative. Indeed, a good working definition of practical creativity ought to emphasize the transition from a state in which something was unforeseen to a state in which it is compelling. Many innovations seem obvious with hindsight because they are compelling to their users.

An Economic Definition of "Technical Progress" with Implications for Creativity

The economic definition of "technical progress" is broader than the word "technical" suggests. Hence my focus on creativity goes beyond the technical. The definition of technical progress is relative to the "production set" in the space of all the inputs (labor, capital, energy, clean air) and outputs (houses, iPods, music, etc.) we care about. Any increase in knowledge that expands the production set to permit the better satisfaction of human desires with the same inputs or the equal satisfaction with less input counts as "technical progress." This is an explicitly consumerist definition, so product quality improvements—seen from the buyer's perspective—count as technical progress.

The sense of "inputs" is inclusive. For instance, they include the quality of the earth's atmosphere, so that knowledge which would let us create the same goods and services while putting less carbon into the atmosphere counts as technical progress if atmospheric carbon presents a long-term problem. This example also shows that the value of different kinds of technical progress is contingent on the availability of different inputs. Assuming that the climate scientists are right, and that the carbon-carrying capacity of the atmosphere is much less than was once thought, the atmosphere is now a scarce input, and technical change that permits fulfilling human needs while putting less carbon into the atmosphere is newly valuable.

The several industrial revolutions, which focused largely on the manipulation of physical objects in manufacturing and mining, or the mechanization of farming, which also focuses on physical manipulation, are easily perceived as technical change. Less obvious is that the installation of a corporate enterprise's new resource-planning system, which focuses on the work of a large white-collar bureaucracy, is technical change. The economic perspective is useful here. At the time of the first industrial revolution in the eighteenth century, the growth bottleneck facing the economy was the amount of physical goods that could be produced by muscle labor (human or domestic animal). Similarly, at the time of the second industrial revolution in the late nineteenth and early twentieth centuries, the automation of the work of blue-collar workers relaxed a growth bottleneck and permitted society to have more while working less (and using less of other resources). Today, many more people in the rich economies work in white-collar bureaucracies than (directly) in manufacturing, mining, or agriculture. If we are to have more output with less input (less labor, less carbon, etc.), one task for technical progress is the automation of white-collar bureaucracies.

Entrepreneurial creativity in the age of automating bureaucratic work has had, and continues to have, a particularly hard task. For a variety of reasons, seeing overlaps between feasible technical improvements and the creation of new economic value in this sphere is extremely difficult. This fact makes supporting entrepreneurial creativity all the more important.

Definitions of "Innovation" and "Invention"

Technical progress in the economic sense involves a number of different kinds of creative endeavors.[5] Here we focus on the exploitation of science and engineering to drive long-run economic growth. This process involves three very different creative activities: invention, innovation, and diffusion.

Precise definitions of these three activities are the subject of some debate, but the key distinctions are as follows:

Invention: The conception of new scientific or engineering ideas.

Innovation: The development of new marketable products or new usable processes.

Diffusion: The adoption of new products or processes widely in the market.

Each of these activities involves creativity; innovation and diffusion involve entrepreneurial creativity.

Invention

Invention is what most people have in mind when they think of technical change. It is a varied activity, including basic science, applied science, and engineering. It occurs in a variety of disciplines, or in no discipline; it may draw on knowledge from multiple disciplines; and it is found in academic life and companies. The key point for the purpose of this discussion is that invention is technical in the narrow sense.

A closely related idea is the technical knowledge stock of the economy, which is increased by invention. Invention creates new knowledge, which is added to the stock. To understand the relationship between entrepreneurial creativity and invention, I focus on two aspects of the technical knowledge stock—that is, accumulated inventions.

First, not all of the technical knowledge stock of the economy is known to everyone. Much of scientific and engineering knowledge is open, of course. When invention occurs in academic life, or when we academics capture the knowledge of inventors in commercial life (i.e., theory catches up with practice), technical knowledge becomes part of the knowledge stock of the economy. But this does not mean that everyone knows it; often, only specialists do. Invention in commercial life often remains private, becoming part of the knowledge stock of a company (and in that limited sense, of the economy).[6] The key point for understanding its relationship with entrepreneurial creativity is that accumulated scientific and engineering knowledge is distributed in society. The more open the access to scientific and engineering knowledge is, the easier for the distribution of knowledge to change and for entrepreneurial creativity to be sparked; but this is not the same as saying it is infinitely easy.[7]

Second, a distinction must be drawn between scientific and engineering inventions and new inventions that are technically feasible. Although the stock of scientific and engineering knowledge is largely codified and maintained in excellent order, knowledge of which potential new inventions are technically feasible is distributed among technologists in a very different way. Some potential new gains in scientific and engineering knowledge call for tremendous creativity. Others are advances that any reasonably well-trained engineer can see to be technically feasible. Between these extremes lies a great variation in knowledge about potential inventions, and in the degree to which this knowledge is distributed in society. Some potential inventions can be foreseen by any engineer if exactly the right question is asked. The distribution of scientific and engineering knowledge about which inventions are technically feasible in society leads us naturally to entrepreneurship, for it is one of the roles of the science- or engineering-based entrepreneur to know which inventions will be valuable and to inquire, with adequate specificity to permit practical engineering, whether they are technically feasible.

Innovation

The key difference between invention and innovation is that innovation is market-facing. The watchwords of innovation are “marketable” and “usable.” Thus, innovators are typically focused on very different values from inventors, notably on implementation, speed, and cost.

To a process innovator, the fundamental question is whether the process works, whereas a product innovator wants to know whether the product will sell.

Innovation is not concerned, unless it is compelled to be, with generality, clarity of statement, or even correctness (beyond reasonable empirical assurance that its results are going to work or sell). In the process of innovation, the invention of new technical knowledge is a cost, not a benefit. To be sure, the best way to innovate sometimes involves invention, but new knowledge is not innovation's goal: new products and processes are. Yet even when no invention is involved, innovation is a creative activity.

Innovation, because it uses technology to fulfill an external need, is fundamentally about overlaps. Whether undertaken by large firms or small, new firms or old, innovation involves entrepreneurial creativity.

Diffusion

Even after a product or process has been commercialized, users may not adopt it immediately. The diffusion of important new technologies is typically a slow process. Indeed, economic studies that decompose aggregate technical progress into its components put enormous weight on diffusion.

What does diffusion have to do with creativity? Sometimes the slow pace arises because users' adoption of a new technology itself calls for invention or innovation (by the user). For example, the diffusion of computing in commercial environments (accounting systems in one era, electronic commerce in another) is far slower than the diffusion of computing in technical environments (scientific laboratories, factory engineering) because of the organizational innovation and invention needed to make effective use of computing. It is one kind of creativity to invent the computer, another to invent enterprise resource-planning software, and yet another to create value for a specific firm while installing that software. The last class of creators—those in the individual firms installing the software—are very important from the perspective of economic growth.

The market-facing work of innovators sometimes speeds up existing diffusion processes by making adoption or adaption of new products and services easier or cheaper. For substantial transformations, however, innovators must trigger new diffusion processes.

Long-term studies tell us that 3 percent a year is a very good rate of technical progress (increase in generalized output per unit of generalized input) for a rich economy.[8] One reason this figure has not increased secularly, and may soon be decreasing, is that diffusion of important modern technologies, especially of the business data-processing technologies that support white-collar automation, is slow.

Invention, innovation, and diffusion are each necessary and complementary for technical progress. The question of which of them is most important is delicate, as it always is in the case of complements. A causal definition of "most important" fails with complements. Take away any one of the three—invention, innovation, or diffusion—and the other two are unproductive. That said, one definition of "most important" is that it requires the most resources. Another is what requires the most difficult creative steps to achieve. If creativity is highly rewarded economically, these two definitions coincide.

From the Integrated Circuit to the Personal Computer

Several themes of this chapter are illustrated in the series of entrepreneurial inventions and innovations that began with the invention of the integrated circuit (IC) in the 1950s and in due course led to the widespread use of personal computers (PCs) in the 1990s. By examining this series, we see the role of entrepreneurial creativity in the founding of a number of very important industries and markets, the complementary roles of technical creativity in invention and entrepreneurial creativity in innovation, and the nature of the institutions that have supported the entrepreneurial creativity.

As is obvious, from the perspective of economic growth, the discovery of the transistor effect in 1947 was one of the most valuable pieces of twentieth-century science. But much of the economic value derived from practical use of the transistor effect has emerged from the subsequent invention of the IC and the large number of markets and industries that entrepreneurs created in taking advantage of the innovative opportunity.

The IC is a very important general-purpose technology (GPT), and has the main technical and market characteristics of a GPT. Different kinds of ICs have been useful in a wide variety of devices. Some of those devices are themselves GPTs, notably the computers and telecommunications equipment underlying advances in information and communications technology. ICs today are found everywhere and are linked to important and valuable innovation. Moreover, the IC has been open to continued rapid technical progress, enabling ever more powerful, cheaper, or less power-hungry devices, as well as a widening range of devices. Just as ICs have enabled much innovation, the creation of new markets and new industries has provided the funding for round after round of improvements in ICs. Such are the hallmarks of a GPT.

A number of other features of the IC are relevant to understanding the role of entrepreneurial creativity in realizing the tremendous gains that have flowed from it. First, ICs are manufactured with substantial scale economies, and these scale economies are dynamic because there is learning by doing in manufacturing. The one-hundred-millionth unit of any particular IC design is likely to cost far less than the one-thousandth unit. In the language of economics, learning by doing means that the marginal cost of manufacturing falls with volume and falls over time. Second, the IC requires complementary innovation and investment to be useful (in this respect it is a “pure” GPT). ICs alone are useless; to be useful, an IC must be designed into an electronic device. Electronic devices, in turn, are often useless without complementary innovation. A computer without applications software, for example, is no more than a "boat anchor," in the dismissive industry phrase.

To show these important results linking entrepreneurial creativity to value creation, let us look at only a subset—albeit the most valuable subset—of the innovations and inventions that stemmed from the IC. An important feature of the founding of Silicon Valley in California was the complementarity between the technical invention of the IC in the late 1950s and a number of entirely managerial and commercial innovations. One of these, which was extremely valuable, was the innovation of a pricing model: bottom-of-the-learning-curve pricing.

The combination of technical inventiveness and commercial and managerial innovation around the IC led to a wide range of complementary inventions and innovations. To make the market point we need not follow all of these. Instead, we can once again follow the money through the invention of the microprocessor, the creation of the PC industry, the invention of the spreadsheet and the word processor, and the innovation of the IBM PC. The IBM PC diffused widely into corporate white-collar work, supporting "individual productivity applications" and creating tremendous economic value. I emphasize this path not because it is the only possible route that could have led us to the highly valuable cluster of markets in the PC industry, but because it shows us the essential role of entrepreneurial creativity and the set of supporting institutions, notably market institutions, that enable it.

The Founding of Silicon Valley

The differences between scientific creativity and entrepreneurial creativity—and their complementarity—emerge from a famous example of how scientists migrated into entrepreneurship and became technologist-managers.

Many people know of how a brilliant physicist, William Shockley, attracted a number of other brilliant young scientists, including Gordon Moore, Robert Noyce, and Andrew Grove, to his entrepreneurial firm. The creative ideas behind the semiconductor industry at that time were quite new; Shockley's Nobel Prize was awarded (to him and others) in 1956 "for their researches on semiconductors and their discovery of the transistor effect." After a dispute, a number of the younger scientists left Shockley Semiconductor in 1957 to found Fairchild Semiconductor inside a large, established, electronics company. Later, they left Fairchild to form a start-up, Intel, which is with us today.[9]

Many people also know that an extraordinary number of scientists and engineers learned how to be entrepreneurs at Fairchild Semiconductor. The firms they founded formed the backbone of the Silicon part of Silicon Valley.[10] This string of start-ups—many founded as spin-offs from Fairchild—also led to the formation of the venture capital industry of Silicon Valley, another institution that is still with us today.

Turning Technologists into Technologist-Managers

It is worth understanding what those scientists and engineers learned at "Fairchild University" and how this knowledge was useful in their entrepreneurial creativity. According to Moore, who went on to head Intel, they learned to be "technologist-managers." This change called for a great deal of retraining. First, the would-be technologist-manager had to learn to be less interested in the fundamental intellectual concerns of science. As Moore wrote in 2001,

> [T]he technologist-manager had to learn to guide innovation with an understanding of both commercial and technical goals. These managers needed first to be scientists with a deep understanding of the subject. But the demands of the firm mean that the generality typical of the university style

> lab is far too inefficient. These technologist-managers need to be able to plot the shortest path to workable discovery.[11]

Second, the technologist-manager, even in an area as full of scientific and technical promise as the young Silicon Valley, needed to be attuned to labor-market and product-market concerns. Famously, the founders of Silicon Valley learned *why* they had to be effective people managers from watching Shockley do a bad job of that, and they learned *how* to be effective people managers the way almost everyone does, from experience and practice. Scientists are only very rarely oriented to be people managers in the sense that businesspeople are, and need a great deal of experience to learn the skills. Yet these skills are, as Moore points out, critical to implementation of new innovations.

Product Market Orientation and Seeing the Overlap

One of the most difficult tasks for an entrepreneur is seeing the overlap between (1) what is technically possible with a bit more invention, and (2) what demanders in the market will buy. Innovators need to see overlap opportunities, for that tells them which innovation will create economic value. Ideas about the overlap are the essential feature of entrepreneurial knowledge in technology industries. Many scientists and engineers are very well trained in (1), yet have weak skills in (2). Indeed many people choose careers in technical specialties because, at an early age, they realize they dislike thinking about (2) at all. The ability to see the overlap has some of the features of crossing the boundary between scientific disciplines. But a key difference is that the knowledge about demand in most markets, especially demand for new products or processes, is badly codified and not structured. A mind that is good at grasping the physical sciences is not always good at the soft-studies tasks needed for demand assessment.

However—and this is a crucial point—a scientist or technologist who knows the limitations of his or her own knowledge can found a market in which demand reveals itself. As we shall see, founding a market itself calls for considerable commercial insight, but it saves the scientist/entrepreneur from a great deal of effort in investigating demand needs, or even of learning who the potential demanders might be.

A Network of Firms and People to Train Scientist-Managers

Over a long period of time, a network of knowledge sharing arose in Silicon Valley. One of the great benefits of having a large number of entrepreneurial firms with similar interests in the same region was the growth of this network. The knowledge stock of the IC industry, for example, included not only technical knowledge about inventions, but also market knowledge about innovations.

Entrepreneurs, not all of them working in the same firm, knew (and know) other people to whom they could turn for critical labor-market information ("Should I hire Jo as my marketing person? I know you worked with her," etc.) and product market information ("Which standard will emerge as the market leader?" etc.). This market knowledge is not generally shared across companies in the same way that scientific and technical knowledge is. But market knowledge is no less important to an entrepreneur than scientific and technical knowledge.

An entrepreneurial firm typically has important resource constraints, and thus its ability to undertake complex market research may be limited. Cultures able to support entrepreneurship, such as the open flow of scientific information, open systems, and regional clusters, can lower the costs of founding a successful entrepreneurial firm.

Although I have picked hardware examples from the earliest days of Silicon Valley to illustrate the importance of management and implementation of a conceptual change away from a scientific to a commercial perspective, and of product and labor-market knowledge, the story of software is much the same.

Commercial Innovation to Encourage More Inventions by Customers

Let us return to the specific economics of the IC industry, and the issues raised by and opportunities created through learning by doing—in particular the innovation of bottom-of-the-learning-curve pricing. The IC itself was apparently independently invented by Jack Kilby at Texas Instruments and Robert Noyce at Fairchild (which eventually became Intel). That story is well known. Less well known is that Noyce also innovated bottom-of-the-learning-curve pricing.[12] The problem of selling a new IC is that, at first, before learning takes place, costs are very high. A firm that looks to its accounting system in order to guide pricing will, accordingly, set high prices. Noyce's insight was, first, that if volume could be generated for an IC, the seller could go down the learning curve and have lower costs and, second, that charging prices consistent with those lower costs from the beginning could induce a demand for volume. Essentially, the new firm lost significant money to begin with, but made it back once the volume had built up.[13]

Of course, a variant of this economic logic works for any new product with scale economies. What is unusual in the case of scale economies involving learning by doing is that to achieve the prices that will permit large volume demand, the seller must first produce in large volume, which gives the seller a particularly strong incentive to find a way to discover demand.

Bottom-of-the-learning-curve pricing worked out very well for Intel. It was particularly effective in creating demand that the IC seller had never even imagined. This was an innovation, and an entrepreneurial one, for it called for insight not only into the economics of the firm's costs over time but also into the potential demand for ICs, and specifically into the problem that the potential demand was unknown and unknowable.

A substantial advantage of this pricing solution is that it did not require Intel to know the identities of its future volume customers or their planned volumes. This is an important distinction in terms of the amount of entrepreneurial knowledge required. Consider the most common alternative solution to the problem: to seek out large customers. In the early stages of the IC, they were primarily defense/government customers or large, established electronics firms. Texas Instruments, for example, signed up IBM and many government customers. This solution works if demand is composed of key large customers who can be identified. Bottom-of-the-learning-curve pricing, in contrast, enables the seller to locate many small customers, who may be previously unknown to the seller. This will be particularly important when customers themselves are entrepreneurial firms that are yet to be founded, or firms that are not yet interested in the new technology (ICs)—or more generally, when there are important costs, such as search costs, of linking together the new technology with its users or with inventors of complementary technology.

A second, related strategy, that of volume discounts, also helps a seller hoping to go down the learning curve avoid the need to know its customers in detail. Intel early on adopted a system of volume discounts in order to give customers, including unknown customers, an incentive to design electronic devices that would sell in volume. This commercial innovation was also suitable at the time of its adoption for the limits of entrepreneurial knowledge. Again, an essential point here is that Intel did not need to know why a particular customer would want volume or even how much that customer might want. The volume discounts set up the possibility of an arms-length, market, win-win situation, in which the customer made a large number of devices and Intel sold that customer a large number of IC components.

Another very important example of this approach comes under study in a moment, but here let me point out that these business innovations—bottom-of-the-learning-curve pricing and volume discounts—economize on entrepreneurial knowledge. Intel did not need to know which kinds of electronic devices would serve which kinds of demand. The company could leave that very difficult problem to its customers (the manufacturers of electronic devices) and its customers' customers (users of electronic devices). This market strategy was designed for finding an overlap between technical opportunity, the IC, and value creation, as opposed to a contractual strategy in which buyer and seller agreed up front on large volume.

Recombination

This particular pricing structure was supportive of what is known as recombination. *Recombination* is defined as taking ideas and inputs that already exist and putting them together (possibly with the addition of further invention or innovation) to accomplish something new. Although the commercial use of scientific and engineering knowledge is an extremely varied activity, economists and historians of technical progress noted long ago that most innovation is recombination. For example, Joseph Schumpeter wrote in 1939 that most "innovation combines components in a new way, or that consists in carrying out New Combinations."[14]

Recombination can be extremely difficult to foresee, and the searches for partner technologies with which to recombine are notoriously difficult.[15] By putting the ICs they were manufacturing out in the market at attractive prices, Intel reduced those difficulties for potential customers—who flocked to Intel. Noyce's bottom-of-the-learning-curve pricing was an open invitation for customers to recombine ICs with other inventions and innovations to create new marketable products. This was an inspired decision, since without that recombination we would not have a large number of useful IC-based technologies today. Yes, a pricing scheme can be an "inspired" innovation!

More generally, a market strategy encourages recombination by unknown, future inventors and innovators. In a new technology and market area (such as the uses of ICs, which were clearly a broad field, but one as yet entirely unexplored), enabling and encouraging recombination could create a large amount of value. The commercial innovation of a firm making a GPT, of building a market and setting it up to accommodate innovation by new partners, contributes to the environment supporting new entrepreneurial creation.

Recombination and Reuse within the Firm and across Customers

With many tens of thousands of different kinds of integrated circuits now in use, the IC is clearly a GPT. But so, too, was the IC when it was first invented. The volume of an IC's production that was consistent with going down the learning curve and achieving low costs exceeded the volume needed by any particular customer. And if every new customer needed a custom design, the costs of that design would need to be recovered.[16] The best economic return and the best value creation would occur if ICs were designed to be general, at least to some degree. Generality/fit tradeoffs began to matter.

This called for strategies to reuse the same IC design in multiple customers' devices. Early on, an important solution arose: programmability. Products like programmable read-only memory (ROM) and its various improvements and descendants (EPROM, EEPROM, and others) pushed out the envelope of reuse of a single design. As everyone now knows, the most important invention in terms of programmability was the microprocessor.

It is worth pointing out that the microprocessor, the "computer on a chip," was not invented to create the personal computer. It was invented to permit reuse of the same design across multiple customer products, actually digital watches. But the invention of the microprocessor was about to be turned into one of the most valuable pieces of twentieth-century technical progress, leading, together with a large amount of entrepreneurial creativity, to the founding of a large number of firms and industries. The generality in the microprocessor did not anticipate, direct, or compel the further market in entrepreneurial creativity. It enabled and permitted it.

The Personal Computer: Entrepreneurial Creativity Founds an Industry

Around the time of the invention of the microprocessor at Intel, a number of different entities were trying to create a personal computer, that is, a computer that would be used by one person.[17] None of these efforts was succeeding commercially (though some were technically impressive). None led to the founding of the PC industry, or to mass markets in computer hardware and software. The problem was the lack of entrepreneurial knowledge, that is, the lack of an overlap between a complete computer system—hardware, software, applications, and peripherals—that could be designed and built to make a computer system that a large number of people would buy. In short, entrepreneurial knowledge was scarce and valuable.

At this point in the discussion, several of the key features of entrepreneurial creativity came together to ignite a process that created enormous economic value. Soon after their invention in the early 1970s, Intel microprocessors were available with volume discounts and bottom-of-the-learning-curve pricing. The point of this was, as pointed out earlier, to enable potential customers to invent or innovate in ways that would use a large number of Intel chips in ways that could not be foreseen. While putting the computer on a chip into a computer was a technical advance that now seems obvious, there was nothing obvious ex ante about the commercial innovations that led to the founding of the PC industry. They combined creativity from a large number of sources.

Ed Roberts at Micro Instrumentation and Telemetry Systems (MITS) offered the first successful PC kit, the Altair—the device on the cover of the January 1975 edition of *Popular Electronics*. The immediate market was the kind of people who read that magazine: technically fluent users who would be called, in the language of the early PC industry, "hobbyists." There is a heated dispute about who invented the PC,[18] which is irrelevant from an economic growth perspective. Roberts's combination of the invention of a particular PC kit and the innovations associated with pricing and marketing it founded an industry.

What were the key creative elements in his introduction of the Altair, and how did they draw on the earlier entrepreneurship at Intel? Roberts was commercially oriented, and he knew how to get the message out to a number of relevant customers; the magazine cover was a coup. Further, because of Intel's pricing schemes, Roberts was in a position to sell a kit from which one could assemble a working computer for less than the single-unit price of a microprocessor. He bought the microprocessors in bulk, taking advantage of the volume discount, and thus was able to offer his customers a low price. Roberts knew he would succeed only if he could sell a significant number of kits, but his success built volume for him and, of course, ultimately for Intel to an extraordinary degree, since Intel microprocessors can now be found in hundreds of millions of PCs. In the short run, though, the problem was to finance a volume purchase of microprocessors and to create a mass market.

Roberts would later say, "We were lucky to have a banker and a magazine who believed there was a real market."[19] The "real market" was then counted in hundreds of computers, not the later tens of millions. Still, this was the finance and the publicity that ignited the industry. Aspiring entrepreneurs, and anyone who studies entrepreneurial creativity, could learn much from his focus on using a publisher to create a market presence and his willingness to work with any appropriate source of finance, not just venture capital.

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To hammer home one of the analytical points of this chapter, there was much more than one piece of entrepreneurial creativity at work here. The founding of the PC industry turned on not only the creativity of an innovative device supplier, Altair, but also on the creativity of inventive and innovative component suppliers like Intel. One central point of the component suppliers' innovativeness was to permit, rather than to attempt to direct or to anticipate, invention and innovation by their customers. They went to particular lengths to encourage innovations and inventions that would build large-volume businesses. The PC business, as we now know it, is a mass-market volume business. That development required the alignment of entrepreneurial creativity from a number of different inventors and innovators. Many of the key innovations were market-building. Others were an invitation to create follow-on innovations and inventions. The nascent PC industry, to a considerable degree, constructed for itself an environment in which many different inventors and innovators, each with some—but not all—of the relevant entrepreneurial knowledge, were able to contribute to setting a high rate of technical change and a direction of technical change leading toward economic growth.

Two Senses of Complementarity

Many writers emphasize a different linkage across entrepreneurs, that is, the role of one entrepreneurial firm in spinning out others. Many, many firms—celebrated as “Fairchildren”—spun off from Fairchild. From those in turn, and from other early firms, a large number of other start-ups were spun off. The spin-off mechanism is an important source of entrepreneurial firms, of course, and the management literature is right to emphasize it (though it sensibly emphasizes spin-offs from established firms). As long as one is focused on the origins of firms, this perspective is important.

But if one is interested instead in the origins of markets and industries, as I am here, one needs a different notion of complementarity, more related to open systems and markets. I emphasize a separate linking mechanism between different firms in which one inventive or innovative firm sets up market relations to encourage the entrepreneurial creation of other firms and technologies. The linkage of a series of complementary inventions and innovations can find an overlap between technical opportunity and value creation enjoyed by no one individual. That is the power of entrepreneurial creativity in founding whole industries, and it centers not on the individual entrepreneur's effort to solve all problems but on leaving open opportunities for invention and innovation by others. Both critical IC firms like Intel and critical PC firms, like MITS, followed this path and thus launched an industry.

THE TRANSFORMATION WROUGHT BY ENTREPRENEURIAL SOFTWARE

Any computer, including the PC, is only as valuable as the software available for it. To underscore this point, consider the uses of early PCs. The creation of the Altair quickly led to the founding of entrepreneurial programmer-tools firms, of which some, such as Microsoft (then Micro-Soft) are still with us. Early software categories for the PC—also to a large degree the product of entrepreneurial creativity—primarily served hobbyist or other technical demand categories. Here we can see one of the great strengths of entrepreneurial creativity in a new industry with limited barriers to entry (because of open systems). A wide variety of software products came into existence to serve the existing market of hobbyists and the like.

The hobbyist market looked large to the entrepreneurs who flooded into the PC industry in the late 1970s. But it was vastly smaller than the PC's eventual market. Before long, the PC would be a near-universal tool in white-collar work and serve many other markets as well.

Entrepreneurial creativity in software was critical to the transition. It was thus essential that the leading firms in the early PC industry also followed open-systems strategies. There were a number of leading firms in the early days, but by 1977 two clear leaders had emerged, Digital Research Inc. (DRI), which supplied the CP/M operating system running on a large number of computers, and Apple, which supplied both the Apple II and its operating system. Both companies encouraged a wide number of software vendors to write for their computers, pushing information out to software vendors about systems calls. The result was an explosion of software, including software from creators whom the industry's founders did not know. The system, by which entrepreneurial creativity enabled further entrepreneurial creativity, was thriving.

This system involved recombination both in an intellectual sense (the reuse of existing ideas in new domains) and in a market sense: the extension of the PC itself to wider and wider domains of use. Many of the firms took existing technologies and reworked them to be effective components of a small computer. For example, the firm then called Micro-Soft rewrote the existing Basic language to work on a very small computer. This called for new invention in the form of "tight code" and the addition of features that made the inventors of Basic very angry but which sold a great deal of software. Yet it also clearly recombined existing knowledge. Many other entrepreneurial PC firms of this era made similar recombinant inventions, involving engineering and entrepreneurial creativity. Some version of the relevant ideas existed for large computer systems; the entrepreneurs needed to create versions that would work in the PC market, which was a different environment technically (hence the tight code) and was also a radically different market (a PC needed to cost two orders of magnitude less than a big business data-processing machine).

Of the important innovations and inventions in software for the early PC, two stand out as transformative from an economic perspective. The invention of the spreadsheet and the word processor opened up new markets for themselves, of course, but also for the PC, which white-collar workers could now use. This was a very important step in locating the overlap between the technical opportunity represented by the PC and value creation. Tens of millions of PCs were eventually sold for white-collar workers' use.

It may seem incredible to modern observers that a great deal of entrepreneurial creativity was required to see the PC as a machine someone would use at his or her office desk. But the fact is that the earliest participants in the computing industry did not see the important of white-collar work in the demand for PCs. Nevertheless, they built their new industry in an open-systems way so that others could find the overlap. Just as bottom-of-the-learning-curve pricing was an invitation to recombinant technical change, so were open systems.

Let me add one last step here: the innovation of the IBM PC. The IBM PC was not much of an invention, in the narrow and technical sense of that term, as it was basically a CP/M machine, albeit a very good one. The IBM PC had some user interface improvements over the average-practice CP/M machines of the time, such as function keys. But PC-DOS, the operating system that ran on the IBM PC, and the ancestor of modern Windows, was a clone of CP/M. As an innovation, however, the IBM PC was extremely important. IBM's marketing legitimized the PC as a machine that corporations could use. The market for PCs in white-collar automation exploded after its introduction.

Some Lessons

Perhaps the most important lesson of this discussion is that the scope of important innovation is not limited to technical advances. A second really important lesson has to do with recombination and the accumulation of knowledge. Institutions can be set up as parts of markets to encourage entrepreneurial creativity. As a result, almost like a miracle, a large number of uncoordinated entrepreneurs, working in markets, can invent something of great value for users whom they do not know.

The invention of the IC might appear to be, at first glance, an example of the linear model whereby science leads to engineering, which in turn leads to commercialization. Shockley was certainly a brilliant scientist whose scientific work formed the foundation of much that came later. However, other factors were—as they usually are—an essential feature of the success of the IC in creating large economic value. The discovery of the overlap between demand needs and technological opportunity was a joint effort, distributed over a large number of entrepreneurs and established firms. This discovery created a revenue flow that permitted IC firms to make the increasingly expensive investments needed for further advances. The software entrepreneurship caused the fundamental advances in the IC, as much as the reverse. Indeed, the founding of the PC industry was very far from following the linear model. It started in a market process whereby entrepreneurial creativity saw opportunities to use existing technical progress to serve demand opportunities; it grew through a market process where *other* entrepreneurial firms saw new demand opportunities and created powerful profit opportunities for the invention of new and better technologies.

Today we are living in another era of valuable and diverse entrepreneurial creativity in markets. The founding of new industries online, on mobile devices, and in social networks is the result of a market process of entrepreneurial creativity. At the moment, much of the innovation in these areas creates economic value through new forms of entertainment and play. What remains to be seen is the scope of entrepreneurial creativity in these new industries. Will new innovation repurpose these technologies away from play and toward the automation of white-collar work, as it did in the PC industry? If so, the economic value arising from this new round of entrepreneurial creativity could contribute a significant fraction of economic growth in this century. The key to such a step will be, as it was earlier, the variety of potential innovators and the open-market conditions conducive to widespread entrepreneurial creativity.

NOTES

1. In emphasizing the entrepreneurial creation of new markets and industries, I follow F. A. Hayek, "Economics and Knowledge," *Economica* IV, new series, no. 13 (1937): 33–54, and the economic analysis of entrepreneurship. There is a related literature on the founding of firms, which is the alternative definition of entrepreneurship. I emphasize the economic over the managerial definition because of its focus on the long-term growth of the whole economy.
2. Of course, entrepreneurs do many other things in the economy. These include driving the small business sector in low-tech parts of the economy, creating alternatives to the corporate form through self-employment, etc.
3. This view of locating overlaps—rather than merely commercializing what has been invented—is an important distinction. The "linear model," in which

science creates something that engineering then makes concrete and companies then sell, has long been discredited empirically. See Stephen J. Kline and Nathan Rosenberg, "An Overview of Innovation," in *The Positive Sum Strategy: Harnessing Technology for Economic Growth*, ed. Ralph Landau, Nathan Rosenberg, and the National Academy of Engineering (Washington, DC: Nabu Press, 2012), 275–307, for a review of the main ideas, and 275 for a strong statement about the problems of the linear model.

4. A discussion of the relative importance of improvements in existing goods and of the creation of new goods can be found in Timothy F. Bresnahan and Robert J. Gordon, eds., *The Economics of New Goods* (Chicago: University of Chicago Press, 1996).
5. There is a multidimensional continuum of types of creative output, from fundamental and basic science at one extreme to art (high or kitsch) at another to the "creative" people at advertising agencies at yet another extreme.
6. Patented inventions are supposed to be a hybrid, in which a single company gets exclusive rights to use of the invention for a period of time while the invention enters the knowledge stock of the whole economy. Often, of course, there is either related nonpatentable knowledge that is not made public ("how-to" knowledge) or some other incompleteness, and part of the invention remains known only privately.
7. Joel Mokyr in *The British Industrial Revolution: An Economic Perspective* (Boulder, CO: Westview, 1999) has made the very important point that comparatively easy access to scientific and engineering knowledge in Britain helped spur the industrial revolution there. Potential entrepreneurs in Britain had access to scientific and engineering knowledge through institutions that did not call for extensive technical schooling, unlike the comparatively rigid French system, which rigorously trained a few specialists (excellently!). The French system sparked considerable invention but, Mokyr argues convincingly, less entrepreneurship than the British one.
8. Much higher rates of technical progress are possible for a short period of time and in economies that are catching up with world leaders.
9. Classic sources include Ernest Braun and Stuart Macdonald, *Revolution in Miniature: The History and Impact of Semiconductor Electronics* (Cambridge: Cambridge University Press, 1978); Paul Freiberger and Michael Swaine, *Fire in the Valley: The Making of the Personal Computer*, 2nd ed. (New York: McGraw-Hill, 2000); and Martin Campbell-Kelly, *From Airline Reservations to Sonic the Hedgehog: A History of the Software Industry* (Cambridge, MA: MIT Press, 2003), the latter book being particularly valuable on software innovation.
10. See, inter alia, AnnaLee Saxenian, *Regional Advantage: Culture and Competition in Silicon Valley and Route 128* (Cambridge, MA: Harvard University Press, 1994), 31, for this history.

11. See Gordon Moore and Kevin Davis, “Learning the Silicon Valley Way,” in *Building High-Tech Clusters: Silicon Valley and Beyond*, ed. Timothy F. Bresnahan and Alfonso Gambardella (Cambridge: Cambridge University Press, 2004), 7–39.
12. See ibid. I agree with Moore’s assessment that this invention was “second only to the invention” of the IC itself.
13. See A. Michael Spence, “The Learning Curve and Competition,” *Bell Journal of Economics* 12, no. 1 (1981): 49–70, for the pricing implications and a competitive analysis.
14. J. Alois Schumpeter, *Business Cycles: A Theoretical, Historical, and Statistical Analysis of the Capitalist Process* (New York: McGraw-Hill, 1939), 88.
15. The classic management model is D. Levinthal, “Adaptation on Rugged Landscapes,” *Management Science* 43, no. 7 (1997): 934–50. A wide literature is cited in Timothy F. Bresnahan, “Recombination, Generality, and Re-Use,” in *The Rate and Direction of Inventive Activity Revisited*, ed. Josh Lerner and Scott Stern (Chicago: University of Chicago Press for the National Bureau of Economic Research, 2012), 611–56.
16. More recently, the creation of computer-aided design tools that can interact with computer-aided manufacturing tools permit an IC designer to hire a manufacturer to build a particular design. At the time of the industry’s founding, however, the market in manufacturing services did not yet exist, as the technical progress and commercial innovation that would eventually enable it were themselves enabled by the invention and commercialization of the IC.
17. Freiberger and Swaine cover this well in *Fire in the Valley*.
18. See ibid.
19. Interview in *Personal Computing* (November–December 1977): 59.

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