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Innovating-By-Doing: Skill Innovation as a Source of Technological Advance

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Technological advance often involves a mix of discrete innovations in products, machines, tools, organization, and skills. An extensive literature has investigated innovation in products, machines, tools, and organization [e.g., Schmookler 1966; Chandler 1977]. A literature on innovation in skill also exists, but it is much smaller. Particularly notable in this literature on skill innovation is the notion of "learning-by-doing" by production workers: increases in skill that follow from direct experience with producing a particular good [e.g., Alchian 1963].

However, the literature on learning-by-doing invariably presents skill innovation by workers as minor and passive and as occurring *after* the introduction of the (really important) innovations in products, machines, tools, and organization. While early writings on learning-by-doing emphasized the development of increased skill by *production workers*, more recent writings have placed greater emphasis on improved products, machines, tools, and organization introduced by *managers* as a consequence of their learning-by-doing [Dutton, Thomas, and Butler 1984; Adler and Clark 1991]. This change in emphasis has further depreciated the role of increased worker skill in technical advance.

This paper claims that, contrary to the existing literature, skill innovation is not always minor and passive and does not always occur only after innovations in products, machines, tools, and organization. Indeed, I argue that some product and process innovations can be directly attributed to innovations in worker skills. I also argue that, in other cases,

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particular technical innovations could not have been achieved without some particular previous skill innovation.[1] As these new skills are often acquired while workers are actively engaged in production, I label this process "innovating-by-doing" by workers.

To show that skill innovation is not limited to particular industries or periods, I consider case studies from a variety of industries and periods. Further, to ease the drawing of a contrast between my claims and the existing literature, I have selected incidents of technical advance that have direct links with the already-existing literature on technological change.

The Rise of the American System

The United States rose to world economic power in the twentieth century on the foundation of mass production. In turn, the technological basis for mass production was laid almost a century earlier by the development of the so-called "American system of manufacture" in U.S. government armories. Developments in government armories during the early 1800s led to the first large-scale factory production of complex mechanical devices using interchangeable parts. Not only was the particular set of innovations that occurred within these armories "important in itself, but it has been hailed as marking the point at which America ceased to be a net borrower of technology from other nations and became a key initiator of technological change. . . . [T]he American system of manufactures represented a radically new direction for technological progress" [Pacey 1990, 146].

Because of its importance, I use the American system as a test of my claim that skill innovation had an active role in technological development. This is a particularly good test case for this claim because the American system is often presented as the first success in the widespread *elimination* of worker skill from the production process through the systematic use of specialized machines [e.g., Hounshell 1984].

Before the American system came to U.S. government armories in the early 1800s, gun production involved skilled craftsmen. Sometimes these craftsmen fashioned each gun individually. However, in government armories a group of skilled craftsmen worked collectively (via the division of labor) in the factory production of guns. For their day, the guns produced in these armories were highly complex mechanical instruments. Only small-scale production was possible in the labor intensive process of shaping each metal and wooden component of the weapon to its final dimensions. Each weapon handcrafted this way was unique, and each had to be assembled by a fitter who filed and shaped the parts of a particular gun so they all fit together well. As a consequence, no two guns made by this process would have parts that could be easily interchanged.

It was this latter characteristic that concerned the federal government. In the field, damaged guns could only be repaired by a skilled craftsman who would fashion a new replacement part, a time-consuming task. The high failure rates of the individual components of these weapons, particularly during battle, meant that military units could quickly find their firepower diminished as guns became inoperative and could not be quickly repaired. But if gun parts were interchangeable, a damaged part could be easily replaced by a spare (interchangeable) part. Recognizing this, the federal government in the early 1800s began specifying that guns produced for U.S. government use had to be made with interchangeable parts.

Federal government-owned armories located in Springfield, Massachusetts, and in Harpers Ferry, West Virginia, produced most of the guns made for the federal government. At the direction of the government, in the early 1800s these armories moved to altering their production processes so they could produce guns with the desired interchangeable parts. This was not a simple procedure as interchangeable part production had never before been accomplished. The many innovations introduced to achieve this interchangeable part production are collectively labeled as "the American system."

The American system had two distinct components. First, it involved the use of a sequence of specialized machinery to replace a particular task or set of tasks once performed by skilled craftsmen. In gun manufacture, machines were introduced to cut off excess material from the initial forged metal components, to shape metal or wooden pieces into their proper form, to drill holes, to cut notches, and to do other tasks once performed by skilled workers. This permitted the armories to achieve high rates of throughput as these machines could perform these tasks much more quickly than could craftsmen using hand tools.

Second, the American system used a set of gauges throughout the production process to facilitate the production of interchangeable parts. These gauges were set by measuring a component that had the desired dimensions, and they were used to make sure the objects being manufactured would match the ideal component. If parts were not being made to specs, adjustments were made to the manufacturing process so that the correct dimensions would be achieved. In principle, the use of these gauges permitted the production of identical, and so interchangeable, parts.

As the story of the American system is told, in the armories gauges were used to constantly reset the specialized machines so each performed its operation(s) in a way that produced an interchangeable part. The machines and gauges together permitted the production of interchangeable parts. As a consequence, the final assembly of the gun required only minor filing of the interchangeable parts so that they fit together properly. As an additional benefit, the use of these specialized machines permitted a pace of production beyond that previously achieved when each weapon was crafted by hand.

Importantly, the use of specialized machines and gauges permitted the armories to dispense with a large part of their costly, and occasionally resistive, skilled labor force. According to a recent account, "As distinct from European practice, where a fitter tailor-made each part, interchangeability meant that parts could be machine processed and assembled by workers who had not been apprenticed in the craft design and making of the ubiquitous specialist machines, fixtures, and gauges" [Best 1990, 32]. According to another account, "The focus of technological change . . . was the large-scale machine production of interchangeable parts that did not require the application of skilled labor in assembly" [Lazonick 1990, 218]. Private gun producers introduced the same system of production with, it is claimed, the same results. In the Colt Armory in Hartford, Connecticut, "no handwork at all was allowed" [Best 1990, 32], while in the Colt factory in London, many "machines requir[ed] hardly any skill from the attendant beyond knowing how to fasten and unfasten the article, the setting and adjusting of the machine being performed by skilled workmen; but when once the machine is properly set it will produce thousands" [Anderson, quoted in Hounshell 1984, 62-3]. The single role of labor seems to have been to be bystanders, and to be bystanders who were replaced by these technological changes.

Or so the common wisdom says. But evidence exists that the above account leaves out an important part of the story. It suggests that these developments in the gun-making industry of the early 1800s actually serve as evidence in favor of the claim that skill innovation has played a critical role in technological advance. It indicates that workers were not mere bystanders, but were critical contributors to the success of the American system.

First, Paul Uselding showed in an econometric study using production and input data that improvement in *labor quality* was "a significant if not major portion" source of productivity advance in the armories during the introduction of the American system [1972, 306]. This evidence is not consistent with the common story that it was during this period that skilled labor was displaced from the armories and that wholesale deskilling was achieved. This finding points to increased abilities of labor as being responsible for a large part of the improvements gained during the rise of the American system.

Robert Gordon [1988a; 1988b] provides more direct evidence for the claim that innovation in skills–innovating-by-doing by production workers–can be central to technological advance. Gordon used archeological techniques that had previously been used to examine the manufactures of ancient civilizations to study the output of the federal armories of the nineteenth century. He intensively studied the tumbler, a critical part of the percussion lock used in small arms, for evidence of how interchangeability was achieved over the period 1820–1890.

Gordon found that from the early to the late nineteenth century, the tumblers manufactured in the armories became increasingly interchangeable: that is, over this period there was a marked decline in the variances of the dimensions of the tumblers. But the source of this increased interchangeability was not the machines used to produce the tumbler. He found that after the machines had finished with the tumbler, the tumbler was still of a quite crude shape and far from the required dimensions. The machines used in the armories were not accurate enough to achieve the required tolerances for a finished tumbler.

The machines used in tumbler production (and the skills of the machine operators) did improve over the period. These improvements permitted a better made component that was less subject to stress when the weapon was fired. However, this was unrelated to interchangeability per se. Throughout the nineteenth century, specialized machines remained too inaccurate to produce an interchangeable part.

The specialized machines introduced to the armories did displace labor. As a first step, the less-skilled part of tumbler manufacture was separated from the more highly skilled part. This, as noted by Babbage, permitted the armories to hire only the minimum number of skilled workers. Second, machines were introduced that embodied the less-skilled part of the labor process. The armories consequently hired unskilled labor to run these machines. The labor that was eliminated in this process was lower-skilled labor–the cutting away of excess metal from a forged tumbler.

The skilled component of tumbler production, however, was not displaced. Indeed, the tumbler achieved the required dimensions only after skilled workmen filed the metal object down so that it fit the proper gauges. The growing interchangeability of the tumbler in the nineteenth century was due to the growing skill of workers using the traditional tools (e.g., files). "The dimensional tolerances and the quality of workmanship *achieved by the artificers* improved continuously along a learning curve. The improvement in product quality attained was primarily due to the superior mechanical skills *developed among the artificers* who made the lock parts, although better organization of work and manufacturing procedures help facilitate development of these skills. Clearly, the skills required to achieve interchangeability in the new system of manufactures was not 'built into the machines' but remained in the hands of the artificers" [Gordon 1988b, 769; emphasis added].

Further, this innovating-by-doing occurred through a collective process. The standard literature on learning-by-doing emphasizes how the repeated use by *isolated* workers of the tools and machines workers wield leads to increased individual worker (and, hence, aggregate) productivity. But communication *among* workers was central to the discovery of the procedures that permitted interchangeable part production [Gordon 1988b, 759; see also Hodgson 1989, 84-86]. The tumblers produced by different workers in a given armory and, indeed, in different armories appeared to have been filed to final shape by a very similar sequence of strokes. This implies (unless workers working in isolation by an amazing coincidence hit upon the exact same technique) that workers shared their knowledge with one another and agreed on a common best technique to achieve interchangeability.

I am not claiming that increased worker skill alone was responsible for the attainment of interchangeable parts manufacture. Specialized machines did play a role by producing pieces of metal for the workers that were of approximately the same crude shape time after time. By always starting with the same crude shape, workers were likely able to more rapidly discover a set of techniques to transform this piece of metal into the proper final dimensions.

These developments within these U.S. government armories indicate that increased skills can be a source of technological advance. In this case, increased skill led to the attainment of interchangeable parts manufacture. While it is true that machines were eventually made accurate enough to produce interchangeable parts without the use of skilled labor, the initial achievement of this feat was due to workers and their skillful use of gauges and files. According to Gordon, "The new methods of manufacturing metal products introduced in the 19th century not only fully engaged the traditional mechanical skills of artificers but also made new demand on their skills. *The development and learning of these skills took many years and was, in fact, the factor that limited the progress of the new technology*" [Gordon 1988b, 747-8; emphasis added].

The Aircraft Industry

Slow progress in skill innovation can limit the progress of a new technology. In other cases, skill innovation must occur *before* particular advances in machinery and products are possible. I now consider two cases of technological advance from the aircraft industry to illustrate this second point.

It was in the production of aircraft that a stable relationship was first observed between experience and cost. This observation directly contributed to the notion of learning-by-doing. Learning-by-doing, however, is a quite different phenomena from that I am seeking to identify here. Learning-by-doing is a passive learning process *after* some technical advance is already introduced. The skills gained in this learning-by-doing process concern how to manipulate the existing technology more effectively. But the sort of skill innovation I discuss below occurs *before* a technological advance can be introduced.

I start at the beginning with the invention of the airplane. Wilbur and Orville Wright invented the airplane. More precisely, they were the inventors of controlled powered flight. Many others before them had achieved controlled nonpowered (glider) flights and others before them had even launched powered aircraft into the sky. But though these earlier powered aircraft merged adequate lift with adequate propulsion, the pilots of the craft had no way to adequately control the machine once it was in the sky. Once airborne, the craft would set off on a relatively uncontrolled flight until it crashed to earth. The Wright brothers' achievement was to design and fly a powered aircraft that could be maneuvered any direction desired and, eventually, for as long as the craft had fuel. This was the achievement of flight.

Central to the Wrights' airplane was a coordinated control system that permitted the pilot to control the movement of the aircraft in all three dimensions (pitch, yaw, roll). In fact, the patent the Wright brothers took out for their airplane was not for the merging of an airfoil with a propulsion system. This was not patentable as others had before accomplished this task. Instead, the Wrights' patent was for their coordinated, three-dimensional control system [Jakab 1990, 175].

What was also not patentable, but was central to the achievement of controlled powered flight, were the skills of the operator of the flying machine. As Wilbur observed about six months before the Wrights made their first flights, "The soaring problem is apparently not so much one of better wings as of better operators" [McFarland 1953, 330]. Indeed, the Wright brothers "always thought in terms of the final goal of a practical powered airplane, correctly conceiving it as a complex technological system comprising several distinct units, all of which needed to operate in concert to achieve successful flight. This system included not only the physical structure and mechanisms for controlling and propelling the airplane, but also the pilot as an integral component of the craft" [Jakab 1990, 96]. As Wilbur said, "In all of our machines the maintenance of the equilibrium has been dependent on the skill and constant vigilance of the aviators" [McFarland 1953, 328].

The Wrights saw that the key to developing a true aircraft was developing the skill of flying–a skill that before them did not really exist. However, this learning did not occur passively after the Flyer was constructed. The Wright brothers learned how to develop and fly their three-dimensional control system while flying a glider.[2] The development of the three-dimensional control system, as well as the development of the skill of flying, had to be invented *before* the Wright brothers could construct a successful powered aircraft.

Later events make this clearer. After the first flight of their Flyer, the Wright brothers did not try to manufacture and sell their type of aircraft. They knew that they had not yet developed an adequate control system that would let other pilots adequately control their aircraft in the air. While they had invented flying and the flying machine, they had not yet created a commodity that they could sell because they had still not perfected the skill of controlling their aircraft. Therefore, after the initial successful flight in 1903, they continued to develop their invention. These developments were of three types: the machine itself (making it larger, giving it more power, permitting two people to ride at once); the three-dimensional control system; and, not less important, the techniques for flying the aircraft safely.

Indeed, the main factor keeping them from marketing their flying machines was an intermittent problem of controlling the aircraft during certain types of turns, particularly during short, tight circles [Howard 1988, 182]. The machine would occasionally stall, and the pilot would momentarily lose control of the aircraft as it plunged toward the ground. Finally, in September 1905 after two years of experiencing this problem, the Wright brothers finally solved it. The development of a new flying technique corrected this problem–turning the nose of the craft downward when it started to stall in a tight turn. According to Wilbur, "The remedy was found to consist in the more skillful operation of the machine and not in a different construction. . . . When we had discovered the real nature of the problem, and knew that it could always be remedied by tilting the machine forward a little, so that its flying speed would be restored, we felt that we were ready to place flying machines on the market" [McFarland 1953, 521].

The achievement of the first flight depended on the development of certain skills, and the creation of a marketable flying machine depended on the further development of these skills so that the machine would be much safer to fly. Consequently, the commodity the Wrights offered for sale was a package that included a flying machine *and* instructions in the skills needed to fly the machine [Howard 1988, 200, 217].

Here, then, is an important case in which a technical advance required simultaneously the innovation of a machine and the invention of a set of skills. The skills invented were required to make the flying machine technically and commercially feasible.

Here, the inventor of the machines and the inventor of the new skills were the same people. However, this need not be the case. Another example, again taken from the aircraft industry, illustrates this point.

Just a little more than 45 years after the Wright brothers made the first controlled powered flight, U.S. aircraft makers turned to designing commercial aircraft capable of flying from 25,000 to 30,000 feet above sea level. Such aircraft could fly much faster and further in the thin air found at higher altitudes than could aircraft restricted to low altitudes. The thin air at high altitudes required the development of large pressurized cabins for the crew and passengers. The design of such a high-altitude, pressurized aircraft was critical if the airline industry was to rapidly expand in the early post-World War II years.

The drawback of such high-altitude aircraft was that a sudden loss of cabin pressure at 25,000 feet exposed all aboard to risk, and the very young and very old to potentially grave risk. If such a loss of pressure occurred, the pilot had no choice but to send the airplane into a steep dive to get the plane down to a safe altitude as quickly as possible. (In the late 1940s and early 1950s, installing oxygen masks above each seat was not economically feasible.) However, such dives to safety led the aircraft to achieve speeds far in excess of what was considered safe, exposing the airplane to the possibility of a midair breakup from air pressure overloads.

Engineers were stymied. They could not reinforce the construction of the airplanes and still have an aircraft light enough to act as a long-distance carrier. And, they could not conceive of any possible way to have the pilot dive the plane to low altitudes as fast as necessary in the case of a loss of cabin pressure without exposing the plane to structural failure. Without a breakthrough on this problem, high-altitude commercial aircraft could not be introduced.

However, a test pilot, Herb Fisher, suggested an unusual maneuver that he believed would permit a rapid but safe descent of the aircraft. He suggested that the pilot reverse all propellers simultaneously while he sent the airplane down into a steep dive. Engineers rejected this maneuver as too risky. They believed that is would likely lead the pilot to lose control of the aircraft or, again, to a midair breakup.

Not discouraged, Fisher showed after a series of test flights with a C-54 in 1947 that the technique would work. It did permit a rapid but safe controlled descent of the airplane. After his demonstration of this maneuver's safety, it became accepted worldwide as the safe way to deal with sudden loss of cabin pressure at high altitude. And, more directly, it permitted aircraft companies to proceed with their development of high-altitude commercial aircraft.[3]

This incident again illustrates that skills do not merely increase passively through a learning-by-doing process after some technology is installed. Rather, as was also the case in the invention of flight by the Wright brothers, certain skills had to be invented *before* a particular technology became technically or commercially feasible.

Innovations in the Steel Industry

Technology today is more flexible and powerful then was the technology used in U.S. government armories, circa 1830 or, even, the technology used in aircraft production, circa 1950. But this does not imply that today skill innovation necessarily plays an unimportant role in technological advance. To make this point, I look at one recent technological change: the introduction of "thin slab technology" in the steel industry in 1989.

Flat rolled steel is produced in three discrete stages. First, molten steel is produced; second, this molten steel is cast into thick slabs; third, these slabs are rolled into sheets 0.1 inches thick. Conventional integrated steel producers use a technology that produces in the second stage 10-inch thick slabs. Turning these slabs into thin sheets requires that, first, these cold slabs be reheated to high temperatures and, second, that they be rolled over and over again. This process occurs in the massive, miles-long steel complexes built by steel producers like Bethlehem Steel and U.S. Steel.

Under competitive pressure, steel producers by the 1980s considered introducing a new steel-making process: thin slab technology. This involved the production from molten steel of 2-inch thick slabs rather than the current 10-inch thick slabs. Further, these 2-inch slabs would be sent directly into the massive rollers of the third stage of steel production. In the existing technology, the 10-inch thick slabs were allowed to cool after they were produced; before they were sent to the rolling mills, these slabs had to be reheated. Thin slab technology would reduce much of this reheating process and, so, use significantly less energy and time than the old technology. The lower energy, time, capital, and labor requirements of thin slab plants would give the firm that successfully introduced this technology a major competitive advantage [Ansberry 1989; Hicks 1989; 1991].

By the mid-1980s, SMS Schloemann-Siemag offered for sale the first machine designed to cast 2-inch thick slabs from molten steel. However, few firms in the steel industry were convinced that this machine would work well enough to make its purchase worth the risk. The technology was still new and unproven. Only Nucor Steel Company was willing to take the $250 million gamble required to build a steel plant based on the SMS caster.

But by 1991, it appeared that Nucor's gamble had paid off. Using thin slab technology, Nucor was able to produce high-quality flat rolled steel at a cost much lower than the conventional steel producers. In the words of a steel analyst, "The technology has proved that it can work" [Hicks 1991, D7]. Of course, it was not easy. "Mr. Iverson [the president of Nucor] is wrestling with a host of unexpected start-up problems. . . . Mechanical and technological difficulties have sent planners back to the drawing board more than once to revise the process" [Hicks 1989, 33].

Preston [1991] presents an in-depth account of Nucor's introduction of this new and unproven technology. This account makes clear that the technology did not autonomously "prove itself" and that many others, besides the company president and "planners," contributed to the success of the new technology. Preston described how workers discovered how to make the new casting machine perform as envisioned by its inventor, by SMS, and by Nucor.

The key to the success of the new caster was the injection system, which determined how fast molten steel flowed into the caster. If the molten steel was injected too fast or too slow, the slab produced by the caster would be flawed. Such a flawed slab could not be turned into marketable flat rolled sheets of steel. More extremely, if the molten steel was injected just a bit too fast or too slow, a "breakout" could occur. A breakout occurs when thousands of pounds of molten steel, at 2,900 degrees Fahrenheit, bubbles or even bursts out of the caster. Such an incident puts all working near the machine at great risk.

Initially, the proper pace of injection and the exact procedures needed to produce a satisfactory 2-inch slab were unknown. They were discovered in the following way: once the initial machine settings failed to work, "we'll punch new buttons. We'll try new settings. We'll try every button we can think of. If nothing works, we'll terminate the cast" [Preston 1991, 208].

Those operating the machine had the responsibility to perform this process of trial-and-error and thereby to discover the exact procedures required to produce a quality 2-inch slab of steel. Just before the first attempt to use the casting machine, the melt shop manager "handed control of the casting deck away to Thompson [the foreman]. From now on, Thompson would make all the decisions" [Preston 1991, 220]. The initial attempt to operate the caster was the foreman's and his crew's "show." In the days and weeks that followed, those operating the new caster discovered, sometimes at grave risk to themselves, the procedures necessary to successfully cast a quality 2-inch thick steel slab.

The sort of learning that took place in this startup is best labeled as "innovating-by-doing." This learning is quite different from the passive, marginal productivity-enhancing activity discussed in the learning-by-doing literature. The caster in the Nucor mill would not work at all (it had a productivity of zero) until those operating the machine figured it out.[4] Even for technology introduced today, skill innovation can play an important role.

A final point should be made here. As those working the machine experimented with the new casting machine, breakouts did occur. Each breakout carried the risk of injury or even death for those operating the machine. The mainstream literature argues that those who take risks and subsequently succeed deserve "entrepreneurial income." It would stand to reason that those who successfully operated the new caster during the startup of the thin slab technology could subsequently lay claim to part of the profits earned by Nucor as a reward for their risk-taking. However, this was not so. Instead, a cut of the profits only went to those who risked their capital; it did not go to those who risked their lives. It appears that successful risk-taking without ownership of capital is not necessarily rewarded. In this light, justifying the profits going to entrepreneurs on the basis that they are merely being rewarded for their risk-taking is somewhat disingenuous.

Conclusion

Since the time of Adam Smith, students of technological change have tended to underemphasize the role of workers' skill innovation as a source of technical innovation and to highlight the role of "philosophers," that is, of scientists, engineers, and inventors. Neoclassical economists have been most insistent in developing this perspective. In this paper, however, I have argued that in *particular* (but not *all*) circumstances skill innovation by workers can be an important source of technical advance. Skill innovation can be directly responsible for certain advances in technology. Other times, skill innovation can be a prerequisite for later technical developments.

Notes

1. It should be noted that the argument developed in this paper differs from the "labor flexibility" literature [e.g., Piore and Sabel 1984], which argues that a high level of skill is required to facilitate rapid product changes [see also Vernon 1966]. It also differs from the "deskilling" literature [e.g., Braverman 1974], which claims that technological change leads to reduced levels of skill required to perform individual jobs.
2. Before the Wright brothers' innovations, control of gliders had generally meant weight shifting--a technique that could not work effectively in heavier powered aircraft. Still others had believed falsely that maneuvering an aircraft could be accomplished effectively by using a rudder like a ship.
3. This description has been based on Caidin [1992].
4. It should be noted that this skill innovation by workers occurred in a nonunion firm with a poor safety record that paid lower than industry average wages and offered little employment security [e.g., Ansberry 1991]. That such a firm would be the site of innovation is contrary to the perspective developed by those who stress the importance of a highly skilled, well-paid, permanent labor force for innovative worker behavior [e.g., Piore and Sabel 1984; Lazonick 1990; Best 1990].

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