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Abstract

In a marvelous but somewhat neglected paper, 'The Corporation: Will It Be Managed by Machines?' Herbert Simon articulated from the perspective of 1960 his vision of what we now call the New Economy the machine-aided system of production and management of the late twentieth century. Simon's analysis sprang from what I term the principle of cognitive comparative advantage: one has to understand the quite different cognitive structures of humans and machines (including computers) in order to explain and predict the tasks to which each will be most suited. Perhaps unlike Simon's better-known predictions about progress in artificial intelligence research, the predictions of this 1960 article hold up remarkably well and continue to offer important insights. ¡P¿In what follows I attempt to tell a coherent story about the evolution of machines and the division of labor between humans and machines. Although inspired by Simon's 1960 paper, I weave many other strands into the tapestry, from classical discussions of the division of labor to present-day evolutionary psychology. The basic conclusion is that, with growth in the extent of the market, we should see humans 'crowded into' tasks that call for the kinds of cognition for which humans have been equipped by biological evolution. These human cognitive abilities range from the exercise of judgment in situations of ambiguity and surprise to more mundane abilities in spatio-temporal perception and locomotion. Conversely, we should see machines 'crowded into' tasks with a well-defined structure. This conclusion is not based (merely) on a claim that machines, including computers, are specialized idiots-savants today because of the limits (whether temporary or permanent) of artificial intelligence; rather, it rests on a claim that, for what are broadly 'economic' reasons, it will continue to make economic sense to create machines that are idiots-savants.

Introduction.

I had the chance to interact with Herbert Simon on only one occasion. But the circumstances were somewhat exotic. Simon and I were among a number of Western scholars invited to a conference in Warsaw in 1988, the year before everything changed. The objective of the conference was to interact with Polish scholars — philosophers, mostly — on the theme of "praxeology," the study of human action. I have vivid memories of sitting at a small table in our shabby hotel drinking terrible Romanian wine and listening to Simon and Donald McCloskey debating the merits of deconstructionism. (McCloskey thought deconstructionism had much to contribute; Simon thought it was the stupidest thing he had ever heard of.) I also remember Simon's general intellectual engagement and wide-ranging interests. He was the only one among us who made an attempt at the Polish language, and he tied to speak to people from his phrasebook whenever he could.

This encounter largely confirmed for me the impression of the man I had gained from reading his work over the years: a searching intellect, great originality, and a willingness to take strong and clear positions. I hope that all these attributes will also show through in this essay, which takes as its reading one of the more obscure works in the Simonian canon. In 1960, the editors of a volume challenged Simon to answer this question: "The Corporation: Will It Be

Managed by Machines?"[1] In this marvelous but somewhat neglected paper, he articulated his vision of what the "knowledge economy" of the future — 1985! — would look like. Perhaps surprisingly for someone given to the most strident predictions of the speedy and inevitable success of artificial intelligence, Simon in this article is clear that computers and humans have fundamentally different cognitive comparative advantages.

> [M]an's comparative advantage in energy production has been greatly reduced in most situations -- to the point where he is no longer a significant source of power in our economy. He has been supplanted also in performing many relatively simple and repetitive eye-brain-hand sequences. He has retained his greatest comparative advantage in: (1) the use of his brain as a flexible general-purpose problem-solving device, (2) the flexible use of his sensory organs and hands, and (3) the use of his legs, on rough terrain as well as smooth, to make this general-purpose sensing-thinking-manipulating system available wherever it is needed. (Simon 1960, p. 31.)

In what follows I explore this notion of cognitive comparative advantage and use it to tell what (I hope) is a coherent story about the evolution of machines and of the division of labor between humans and machines. Although inspired by Simon's 1960 paper, my account weaves many additional strands into a tapestry of my own design, from classical discussions of the division of labor to present-day evolutionary psychology. I touch both on the history of what has been said about humans and machines and on the often fiery debates in artificial intelligence – debates in which Simon was so prominent. But I do not take on the

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[1] The volume was intended to celebrate the tenth anniversary of the founding of the Graduate

difficult task of assessing and appraising those weighty topics comprehensively and fairly.

In the end, my basic conclusion is broadly consistent with that in Simon's 1960 paper. With growth in the extent of the market, we should see humans "crowded into" tasks that call for the kinds of cognition for which humans have been equipped by biological evolution. These human cognitive abilities range from the exercise of judgment in situations of ambiguity and surprise to more mundane abilities in spatio-temporal perception and locomotion. This conclusion is not based (merely) on a claim that machines, including computers, are specialized *idiots-savants* today because of the limits (whether temporary or permanent) of artificial intelligence; rather, it rests on a claim that, for what are broadly "economic" reasons, it will continue to make sense to create machines that are *idiots-savants*.

The division of labor.

At least since the first Industrial Revolution, people have pondered the relationship between humans and machines. How will machines change life and work? How will they change the role of humans? Although many have conceptualized the interaction between human and machine as a progressive displacement of the former by the latter, writers like Adam Smith and Charles Babbage envisaged a far more complex relationship.

School of Industrial Administration at what was then Carnegie Tech.

In Smith's account, production is a matter of discrete tasks or stages, each with its own set of specialized tools. Under the sort of crafts production that precedes the division of labor, the artisan masters and coordinates multiple stages of production and wields a variety of specialized tools. As growth in the extent of the market makes it economical to subdivide labor, the artisans begins to specialize in a smaller subset of operations and tools. To do this, the artisan must now cooperate with other artisans in a more carefully orchestrated way. Workers become complements to one another rather than substitutes (Leijonhufvud 1986). And the coordination function that the artisans themselves once supplied must now be hardwired to a greater degree into the spatial and temporal "interfaces" among specialized operations and specialized operatives. Each operative must make his or her output relatively standardized so that the next operative down the line knows what to expect; and each operative must hand over that output at a predictable time, lest buffer inventories run dry and the entire production process come to a crashing halt.

Smith attributed the benefits of this organizational transformation to three sources: "first to the increase of dexterity in every particular workman; secondly, to the saving of the time which is commonly lost in passing from one species of work to another; and lastly, to the invention of a great number of machines which facilitate and abridge labour, and enable one man to do the work of many" (Smith 1976, I.i.5).

The first source is clearly cognitive.[2] By narrowing their focus, the operatives are able to deepen their skills through learning by doing. Writing a few decades after Smith, Charles Babbage recognized the larger cognitive implications: that the division of labor applies to mental operations in general as much to as to mechanical ones. He recounts the story of the French mathematician Prony, who stumbled across a copy of the *Wealth of Nations* and suddenly realized that he could use the division of labor to calculate logarithm tables[3] (Babbage 1835, chapter 20). Babbage goes further, suggesting that a machine might take over from humans not only mechanical tasks but some of these intellectual tasks as well. What he had in mind, of course, was the never-finished "analytical engine" often hailed as the first computer. (Machines as information processors is major theme to which we will return.)

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[2] Although not perhaps obvious at first, the benefits of less switching among tasks is also at base a cognitive matter, as Henrik Houtthaker explains. "The indivisibility of the individual consists in the fact that, although it may be capable of a great many different activities, it can perform only few activities simultaneously because most activities utilize the same resources and more particularly that coordinating resource which is known as the brain. The larger the number of simultaneous activities, the greater the difficulty of coordinating them and of carrying out each one properly, and the smaller therefore the output from each activity. This applies not only to simultaneous activities, but also to activities that are spread out over time. In the first place some shorter or longer interval is usually needed to switch from one activity to another; in the second place it is usually easier to perform activities that are known from previous experience than to perform them for the first time. All this, the economist will note at once, can be put in terms of increasing returns. We have increasing returns to the extent that, if several activities are replaced by a single one, there is less need for coordination and switching time and more scope for acquiring experience. The output of the single activity may thus be raised above the combined outputs of the several activities" (Houthakker 1956, p. 182).

[3] Ironic indeed that the French needed Smith to teach them the division of labor, since Smith lifted his account of the making of pins from the French *Encyclopédie*.

As an adherent to the British empiricist tradition — and as a good friend of David Hume — Smith believed that the mind starts out as essentially a *tabula rasa* and that differences in ability are the result of learning and not of any innate abilities.[4] But what if people are born with innately different abilities? Babbage pointed out that nature provides as much support for the division of labor as does nurture: unlike crafts production, the division of labor permits tasks to be allocated according to (innate) *comparative advantage*.[5] This famous principle of optimal resource allocation had lately been discovered by David Ricardo. It insists that allocation to tasks should be based not on who is *absolutely* better at the task but on who is *relatively* better. If person A is better than person B at both management and secretarial work, it may yet pay to assign B all the secretarial work if A is relatively better (is "more better," we might say) at management.[6] If

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[4] "The difference of natural talents in different men is, in reality, much less than we are aware of; and the very different genius which appears to distinguish men of different professions, when grown up to maturity, is not upon many occasions so much the cause, as the effect of the division of labour. The difference between the most dissimilar characters, between a philosopher and a common street porter, for example, seems to arise not so much from nature, as from habit, custom, and education" (Smith 1976, I.ii.4).

[5] "We have seen, then, that the effect of the division of labour, both in mechanical and in mental operations, is, that it enables us to purchase and apply to each process precisely that quantity of skill and knowledge which is required for it: we avoid employing any part of the time of a man who can get eight or ten shillings a day by his skill in tempering needles, in turning a wheel, which can be done for sixpence a day; and we equally avoid the loss arising from the employment of an accomplished mathematician in performing the lowest processes of arithmetic" (Babbage 1835, Section II, Chapter 20, paragraph 250.)

[6] Those who remember their Principles of Economics know that "more better" has a precise interpretation in terms of the slopes of production-possibilities curves.

one takes a middle-ground position in the nature-nurture debate, then clearly the division of labor offers benefits of both the Smith and Babbage kinds.[7]

Smith's third source of benefits from the division of labor brings us finally to the topic of machines. By concentrating their attention more narrowly on a smaller set of operations, he feels, operatives will naturally tend to invent devices that makes them more productive. The reason that specialized workers are able to perceive opportunities to successfully mechanize (parts of) their tasks is that, in narrowing the range of tasks and in standardizing the interfaces between tasks, the division of labor makes the work more routine.[8] It is a major theme of this essay that the human worker may need to retain discretion over some operations while delegating the most routine ones to machines. Nonetheless, in the pure Smithian model of the division of labor, the humans themselves become increasingly machine-like.

In the limit, this amounts to what Charles Sabel (1982) has branded *fordism*. It was not really until the early twentieth century that tools and machining techniques were precise enough to allow genuine standardization of

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[7] Phrased this way, it is hard to disagree with the proposition that both nature and nurture matter. As I will suggest below, the issue once again becomes controversial as soon as one asks for specifics.

[8] "It is generally agreed that Adam Smith, when he suggested that the division of labour leads to inventions because workmen engaged in specialised routine operations come to see better ways of accomplishing the same results, missed the main point. The important thing, of course, is that with the division of labour a group of complex processes is transformed into a succession of simpler processes, some of which, at least, lend themselves to the use of machinery" (Young 1928, p. 530).

parts (Hounshell 1984). Such standardization enabled Henry Ford to take Smithian factory production to a new level by means of the moving assembly line and related techniques, which he and his engineering staff had begun implementing by 1913. The Ford assembly process was above all a system, one designed by specialized engineers rather than by the workers themselves. (This is of course another manifestation of the division of labor: the design of production becomes itself a specialized task.[9]) The system effected a complete redesign of production, breaking operations into simple sequences of routine activity that yielded standardized subassemblies.

By transferring control of systemic issues from the workers to engineers and industrial designers, fordism, in the phrase popularized by Stephen Marglin (1974), had rendered workers *deskilled*.[10] We need look no further than Smith himself for the dire implications of what fordist production would mean for the worker: "The man whose whole life is spent in performing a few simple operations, of which the effects are perhaps always the same, or very nearly the

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[9] "All the improvements in machinery, however, have by no means been the inventions of those who had occasion to use the machines. Many improvements have been made by the ingenuity of the makers of the machines, when to make them became the business of a peculiar trade; and some by that of those who are called philosophers or men of speculation, whose trade it is not to do any thing, but to observe every thing; and who, upon that account, are often capable of combining together the powers of the most distant and dissimilar objects. In the progress of society, philosophy or speculation becomes, like every other employment, the principal or sole trade and occupation of a particular class of citizens." (Smith 1976, I.i.9, p. 21).

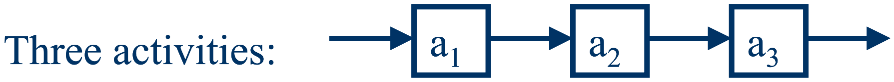
[10] Of course, Marx noticed this long ago. "Intelligence in production expands in one direction, because it vanishes in many others. What is lost by the detail labourers, is concentrated in the capital that employs them" (Marx 1961, Volume 1, Part IV, Chapter XIV, p. 361). On this see also Braverman (1974).

same, has no occasion to exert his understanding or to exercise his invention in finding out expedients for removing difficulties which never occur. He naturally loses, therefore, the habit of such exertion, and generally becomes as stupid and ignorant as it is possible for a human creature to become" (Smith 1976, V.i.178).

Mechanization.

For many, notably those intent on criticizing capitalist work organization, this is pretty nearly the end of the story. In fact, however, it is actually much nearer to the middle of the story. Recall Smith's assumptions. Tools start out specialized to the various activities involved in production, but labor is unspecialized. The division of labor consists in matching the specialization of labor to that of machines. But this doesn't exhaust the possibilities. Why can't *machines* change their level of specialization? (Ames and Rosenberg 1965).

When workers specialize, they reduce the range of activities in which they engage; but, if Smith is right, they also become more competent at the activities that remain. Specializing workers thus trade wide skills for deep skills. Let us for the moment take skill to mean the first concept, skill widening instead of skill deepening. Define skill as the number of activities an operative or machine engages in.[11] Clearly, a crafts artisan is more skilled in this sense than a fordist assembly-line worker. Define specialization as the reciprocal of skill: the number of doers (humans or machines) per activity. By this definition, specialization ranges between 0 (complete non-specialization) and 1 (complete specialization).



Technology.	Workers.	Machines.	Labor specialization.	Machine specialization.	
A	1	3	1/3	1	Crafts production.
B	3	3	1	1	Smithian division of labor.
C	1	1	1	1/3	Volume effect.

Figure 1 Labor and machine specialization.
Source: Ames and Rosenberg (1965).

Now consider a production process involving exactly three activities (a_1, a_2, a_3). The result is a set of possibilities summarized in figure 1. Technology A is what we called crafts production. One worker undertakes all three activities, but machines — which are clearly *tools* in this case — are specialized to activities. Technology B is what Smith had in mind: workers and tools are equally specialized to activities. Technology 3 is the forgotten alternative: workers are specialized, but machines — and now they are indeed *machines* not just tools — become less specialized.

What it means for the machines to become less specialized is that a single device has taken over — has automated — all three stages of production. Many have traditionally conceptualized such automation as a natural extension of the division of labor: each worker wields specialized tools, and automation is just a matter of hooking the relevant tools together (and typically connecting them to inanimate power) so that they run by themselves.[12] As we will see, however, creating skilled machines typically involves redesigning the work process, often in a radical way, so that it meets the needs of machine cognition. As a result, the process may no longer look a lot like a robotic version of the human division of

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[11] The remainder of this paragraph follows Ames and Rosenberg (1965), who offer a more careful definition of terms than I attempt here.

[12] Charles Babbage, for example: "When each process has been reduced to the use of some simple tool, the union of all these tools, actuated by one moving power, constitutes a machine" (Babbage 1835, Chapter 19, Paragraph 225). Similarly Karl Marx, who probably got the idea from Babbage: "The machine proper is therefore a mechanism that, after being set in motion, performs with its tools the same operations that were formerly done by the workman with similar tools" (Marx 1961, Volume 1, Part IV, Chapter XIV, p. 374).

labor. At the risk of drawing a distinction too sharply, we might say that a *tool* is a device that amplifies human skill applied directly to tasks, whereas a *machine* is a device that takes over (often integrated) tasks from the humans, who – as we will see – then direct their skills to tending, maintaining, and designing the machine rather than directly to the production process. A carpenter today still assembles a house with tools, even if those tools are now driven by small electric motors; but plywood is made by a machine. In effect, tools amplify human abilities – both mechanical and cognitive – without fundamentally changing the division of labor.

Machines are another matter. Smith tells us that growth in the extent of the market drives the progressive transition from Technology A to Technology B. But such growth also — and perhaps more importantly — drives a transition from Technology B to Technology C, which we can understand as a further manifestation of the larger division of labor with which Smith was concerned (Langlois 1999a, 1999b). One can see this point illustrated dramatically by visiting the Match Museum in the town of Jönköping, Sweden, which was the "match capital of the world" for much of the nineteenth and early twentieth centuries. In the beginning, the industry took precisely the form Smith predicted. Cottagers in the town and surrounding countryside assumed a variety of subdivided tasks, from chopping and cutting the match wood to folding and gluing match boxes to the debilitating and ultimately gruesome task of coating the tips with chemicals.[13] But what thrust Jönköping to prominence in the industry was not a finer subdivision of putting-out tasks; rather, it was mechanization. In 1844, the brothers Johan and Carl Lundström opened a factory in Jönköping to capitalize on the recently invented safety match, improvements to which Johan had just patented. In 1870 they hired the inventor Alexander Lagerman to further mechanize the process of making matches. Lagerman's machines not only assumed the tasks of humans but — more significantly —combined within their operations what had been many previously separate tasks, and they did so in a way that often differed dramatically from the unmechanized sequence of tasks.[14]

If mechanization takes tasks entirely out of the hands of workers, are we left to infer, with Marx, that the progress of mechanization will inevitably relegate humans to an immiserated proletarian army of the unskilled and unemployed? The histories of the most-developed countries clearly demonstrate

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[13] Which produced phosphorus necrosis in the workers. The transition to the safety match after 1844 had the happy effect of substituting less-toxic red phosphorus for the more dangerous yellow phosphorus (Karlsson 1996).

[14] A more familiar example illustrates the productivity gains to be had from this process. Adam Smith (1976, I.1.3) describes the manufacture of pins in his day, in which ten men, organized according to principles of the division of labor, could make about 48,000 pins a day, or almost 5,000 per person per day. By Marx's era, making pins was already the business of machines, and a single machine could crank out 145,000 a day. One woman or girl could supervise four machines, which means almost 600,000 per person per day (Marx 1961, Volume 1, Part IV, Chapter XV, Section 8, p 460). As of 1980, one person could supervise 24 machines, each making 500 pins a minute, or about 6 million pins per person per day (Pratten 1980). That's a two orders of magnitude increase in productivity in the first century as machines replaced the division of hand labor but only (!) a single order of magnitude increase in productivity over the next century as machines improved.

otherwise. But there are also theoretical reasons to see mechanization as producing quite a different and rather more benignant role for humans.[15]

In Figure 3, the human worker is still specialized, because he or she does only one thing. But that one thing is not any of the original activities; instead, it is the new activity of minding the machine. The invention of the power loom in 1787 increased productivity over the hand loom not only because it could weave faster (by the mid 1820s, at any rate) but because a single person, who was no longer providing the motive power, could operate more than one loom[16] (Landes 1969, p. 86). Of course, we might well view ”tending the machine” not as a single specialized activity but as a complex set of activities – perhaps more complex than the crafts activities the machine displaced. When automatic telephone switches replaced the activities of human switchboard operators, machine tending fell to highly trained technicians and (later) programmers. The backhoe, which replaced the activities of human ditch-diggers, required an operator with greater skill than any pick-and-shovel worker (Robertson and Alston 1992, p. 336). In the telephony case, technological change increased the

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[15] In this respect, Alfred Marshall was closer to the mark than Marx. Machinery, he writes, “constantly supplants and renders unnecessary that purely manual skill, the attainment of which was, even up to Adam Smith's time, the chief advantage of division of labour. But this influence is more than countervailed by its tendency to increase the scale of manufactures and to make them more complex; and therefore to increase the opportunities for division of labour of all kinds, and especially in the matter of business management” (Marshall 1961, IV.ix.3).

[16] Landes (1969, p. 86) reports that “in 1833, a young man with a twelve-year old assistant could run four looms and turn out as much as twenty times the output of a hand worker.”

skill of workers because, as machines took over the more routine tasks, there remained (or were generated) certain complementary tasks to which machines are ill suited and that thus required the ministrations of skilled humans. In the backhoe case, technological change did not lead to a significant redesign of the work process. Instead, more-skilled machines not only aided humans in a skilled activity but actually called forth higher skill in the humans. Thus both skill-enhancing and skill-displacing technical change can be complementary to human skill.

Coordination and buffering.

As we saw, production is largely a matter of the coordination among tasks.[17] And coordination means that each stage must somehow do the right things at the right time: each stage must make decisions that are appropriate in light of the decisions that came before and will come after. A crafts artisan is constantly interacting with and fiddling with the process of production at each step. But when labor is more finely divided, parts become standardized, and much of the coordination among stages is designed into the process.[18] What

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Two looms may have been a more typical assignment, however, until the last quarter of the nineteenth century.

[17] "Production," of course, means more than "making things" in the narrow sense and encompasses all the economic tasks necessary to get a product or service into the hands of the consumer. Indeed, the consumer may also need to engage in some "production" in order to be able to consume (Langlois and Coşgel 1998).

[18] Clearly, increases in the extent of the market make batch production more feasible. In a sufficiently large market, there is a demand for many instances of an identical object, which means, broadly speaking, that the production process for making the object will need to

limits the use of such hard-wired coordination is the complexity and unpredictability of the environment. If a square hole awaits on the assembly line, the production process will work smoothly only if what arrives is always a square peg — and never a round peg, let alone a whale or a bowl of petunias. Indeed, the higher the throughput of a production system, the more vulnerable the system is to spurious variation. If a round peg appears when a square one is wanted, the entire system may come to a crashing halt.

As Simon tells us, there are fundamentally only two ways to deal with an unpredictable environment. "If we want an organism or mechanism to behave effectively in a complex and changing environment, we can design into it adaptive mechanisms that allow it to respond flexibly to the demands the environment places on it. Alternatively, we can try to simplify and stabilize the environment. We can adapt organism to environment or environment to organism." (Simon 1960, p. 33.) Consider the problem of crossing rough terrain —most of the American continent in the early nineteenth century, for example. Like the native Americans before them, the earliest western explorers used Simon's first technique: they took advantage of the adaptive mechanism of the

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make many of the same decisions over and over again. In this respect, we can think of the move to high-volume production as a reduction in *variety* in the cybernetic sense (Ashby 1956). This is implicit in most discussions of dominant designs and innovative regimes (for example Abernathy and Utterback 1978), in which innovation stops being a matter of the trying out of many qualitatively different alternatives and becomes a matter of refining a single alternative. In the language of James March (1991), high-volume production reflects a transition from *exploration* to *exploitation*. As I will suggest eventually, even the phenomenon of so-called mass customization is not an exception.

human locomotion system. They walked and climbed, at least when there weren't suitable rivers available. But once population began gravitating west, it became worthwhile to use the second approach. A steam locomotive is a high-throughput transportation system that works phenomenally well so long as one first prepares the environment in order to reduce variation almost to zero. So the railroad companies altered the terrain — they laid tracks — to accommodate this high-speed, high-volume, but inflexible technology.

A fordist assembly line is like a railroad. It increases throughput by eliminating variation, and thus makes itself vulnerable to whatever variation remains. It is for this reason that such systems need to *buffer* environmental influences (Thompson 1967, p. 20) by placing human information processors between the uncertainty and the high-throughput production process. At the same time that fordism "deskills" assembly-line workers by making their tasks simpler and more routine, it also surrounds those workers (or the machines that inevitably take on the most simple and routine tasks) with a large number of more flexible (more widely skilled) workers at multiple levels — from maintenance workers to top management.[19] Uncertainty and variation can never

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[19] "There will generally be a separate set of skilled manual work departments (maintenance, tool and die making, and special departments that vary with the technology, such as the crew who lay firebricks inside steel furnaces) and skilled staff workers at the managerial levels (engineering, quality control and inspection, scheduling and inventory)." (Stinchcombe 1990, p. 64).

be eliminated; at best they can be pushed “up the hierarchy” to be dealt with by adaptable and less-specialized humans.

As Stinchcombe (1990) sees it, these human “buffers” are information-processing systems that mediate between a complex and uncertain environment and the system in need of predictability.[20] Human cognition can often interpret complex data from the external world and translate that data into the kinds of routine information the productive system can use. For example, a professor translates the complex information on an essay exam into a letter grade that the Registrar’s office can process; a physician translates the complex inputs from observation and medical instrumentation into a diagnosis, which results in a relatively unambiguous set of instructions for nurses, pharmacists, patients, etc.

Human versus machine.

The first industrial revolution improved productivity by assigning the task of providing motive power to inanimate sources like water and steam. The hand weaver became a loom tender. At the same time, machines also began to take over some “relatively simple and repetitive eye-brain-hand sequences” (Simon 1960, p. 31). To the extent that production had been (or could be) laid out as a

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[20] Frank Knight agrees. “In industrial life,” he writes, “purely routine operations are inevitably taken over by machinery. The duties of the machine tender may seem mechanical and uniform, but they are really not so throughout the operation. His function is to complete the carrying-out of the process to the point where it becomes entirely uniform so that the machine can take hold of it, or else to begin with the uniform output of the machine and start it on the way of diversification. Some part of the task will practically always be found

sequence of simple coordinated steps, a machine could perform the steps (perhaps in a slightly different way or in a different sequence) with greater speed and precision. The specialized Smithian match maker gave way to the match-making machine. In the computer era, and especially in the last quarter century, machines have become faster not only at repetitive sequences of tasks in general but at repetitive calculations in particular. We often call such calculation "information processing." If, as I've argued, the human ability to buffer variation is a matter of information processing, will the computer eventually take over from the human buffers — including managers?

What makes this question especially intriguing is that Simon was a champion for the position that abstract symbol manipulation is the essence of thinking, and thus that computers, which manipulate symbols, can in principle be designed to think like humans (Newell and Simon 1961). So we might expect to find Simon suggesting the opposite: that computers will surely begin to outdo humans in many if not all areas involving "information processing." In one sense, this was indeed Simon's view. He makes the characteristically bold claim that,

> because we can now write complex information-processing programs for computers, we are acquiring the technical capacity to replace humans with computers in a rapidly widening range of 'thinking' and 'deciding' tasks. Closely allied to the development

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to require conscious judgment, which is to say the meeting of uncertainty, the exercise of responsibility, in the ordinary sense of these terms." (Knight 1921, III.X.7, pp. 294-295.)

> of complex information-processing techniques for general-purpose computers is the rapid advance in the technique of automating all sorts of production and clerical tasks. Putting these two lines of development together, I am led to the following general predictions: Within the very near future — much less than twenty-five years — we shall have the *technical* capability of substituting machines for any and all human functions in organizations. Within the same period, we shall have acquired an extensive and empirically tested theory of human cognitive processes and their interaction with human emotions, attitudes, and values (Simon 1960, p. 22).

One way to resolve the apparent paradox is to remember that Simon's argument is based comparative advantage rather than absolute advantage. Under this logic, assignment to tasks is not a matter of who is better but, as we saw, of who is "more better." Just as it might be efficient to assign person B all the secretarial work even if A is better at both executive work and secretarial work, it might be efficient to assign to humans the tasks of flexible response and "buffering" even if computers are absolutely better at them, so long as computers are "more better" at routine and well-defined activities. As Simon puts it, to predict that humans will have the ability to make "thinking and deciding" machines "says nothing of how we shall use them." Instead, economics -- not any inherent limits to AI – will determine the division of labor between humans and machines. "Thus, if computers are a thousand times faster than book-keepers in doing arithmetic, but only one hundred times faster than stenographers in taking dictation, we shall expect the number of bookkeepers per thousand employees to decrease but the number of stenographers to increase.

Similarly, if computers are a hundred times faster than executives in making investment decisions, but only ten times faster in handling employee grievances (the quality of the decisions being held constant), then computers will be employed in making investment decisions, while executives will be employed in handling grievances" (Simon 1960, p. 25).

There are many, of course, who would find this a singularly unsatisfying resolution, since it avoids the *sturm und drang* of the well-documented controversy over artificial intelligence. At one side of the debate, Simon always resolutely upheld the strongest version of the thesis that computers can in principle — and will soon in fact — be capable of essentially any cognitive task now undertaken by humans. At the other extreme have stood critics like Dreyfus (1979), who contend that human brains and computers work in very different ways, that the computer is not a good model of human cognition, and that computers will never be able to do what human brains can do. Simon's proclivity for the outrageous prediction has helped keep this pot boiling. My contention is that, far from sidestepping this debate, a bit of economic reasoning (of which the principle of comparative advantage is but one aspect) helps to clarify the issues – and indeed to demonstrate that the debate as it usually plays out is ill posed and misleading.

Clearly, the design of machines is importantly an economic matter. It pays to subdivide labor or mechanize production only when production runs are large enough. What may be less obvious is that the human machine is also in many respects a response to economic forces. The human brain (and the human being more generally) is an evolved product, and therefore one whose design reflects tradeoffs motivated by resource constraints. The field of evolutionary psychology (Cosmides and Tooby 1987, 1994; Pinker 1997) takes as a background premise that, like computers, human beings are information-processing machines, albeit ones designed by natural selection rather than by humans.[21] For scientists in this tradition, understanding the human mind involves "reverse engineering" the brain in light of the evolutionary problem or problems to which that brain proved to be a solution. The mind is thus a computer, designed for the manipulation of symbols; but is also a particular kind of machine, one designed for specific circumstances rather than for pure symbol manipulation in the manner of the digital computer.

Broadly speaking, the crucible of human cognition was the entire legacy of evolution, but critically the last 50,000 years, most of which our ancestors spent as hunter-gatherers. In this reading, evolution produced a mind well adapted to the needs of that lifestyle. Recall that, for Simon, human comparative advantage lies in two areas: (a) sensory, manipulative, and locomotive tasks and (b) problem-solving and decision-making tasks. Both of these sets of capabilities came in handy to the hunter-gatherers, and the two are probably interrelated

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[21] As many writers have pointed out, these design processes may not in the end be so very

both physiologically and in terms of evolutionary trajectory. An upright posture had its advantages, as did the sensitive ability to recognize objects and patterns and to grasp tools and other objects effectively. Having these skills required humans to develop amazingly complex robotics hardware and software.

But human problem-solving and decision-making abilities may have been even more crucial. Humans succeeded by seizing the *cognitive niche* (Tooby and DeVore 1987). In evolutionary competition, species evolve distinctive traits to gain advantage. Their competitors – including their predators and their prey – must rely on evolution to counter that advantage. If lions become faster, zebra cannot immediately improve their agility or their camouflage. Not so humans. Like the Borg on *Star Trek*, they can quickly analyze and adapt to the offensive and defensive weapons of competitors. And they can do so on a time scale that is extraordinary short by evolutionary standards. This ability to learn, adapt, and solve problems in a creative way enabled humans to colonize and master virtually every kind of environment and every part of the planet. What made this success possible was the development of complex symbol-manipulation hardware and software, including language and the ability to amplify individual cognition through culture (Donald 1991).

To Simon, sensory recognition, manipulation, and locomotion constitute the harder problem. "We are much further from replacing the eyes, the hands,

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different (Nelson and Nelson 2002).

and the legs" (Simon 1960, p. 32). Despite some progress, we are still far from duplicating human perceptual-motor abilities more than 40 years after Simon wrote. But what about problem solving and decision making? Simon offered his characteristically bold prediction. "Duplicating the problem-solving and information-handling capabilities of the brain is not far off; it would be surprising if it were not accomplished within the next decade" (Simon 1960, p. 32). We all remember the seventies for many things, but one of them is not the creation of computers that "duplicate" human cognitive skills. Indeed, that may or may not have happened yet, depending on what one wants to count as "duplicating."[22]

So, was Simon wrong? Again, I think the language of "prediction" and "duplication" obscures the real issues, which are that (a) human brains and computers are different machines with different designs and (b) what kinds of information-processing machines get designed will depend on economic considerations. (More on that below) Moreover, that computers can't (yet?) duplicate human abilities in creative decision making and open-ended problem solving is not so much a matter of the failure of computers as it is a reflection of the success of the human brain.

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[22] In a 1994 interview in *Omni* magazine (and presumably elsewhere), Simon held that all of his predictions had come true except for the famous assertion that a computer would beat the human chess champion – and that one was off by only a factor of 4.

It is a staple of fiction that computers and robots are literal minded. When secret agent Maxwell Smart tells his android assistant Hymie to "kill the lights," Hymie pulls out a gun a shoots the light bulb. In fact, computers are literal minded at a much more fundamental level. The reason is that they are completely general symbol-manipulation engines. This can obviously be a great advantage. But it also poses the disadvantage that computers do not find ready at hand all the prepackaged pieces of information and all the purpose-built learning and processing systems we take for granted as "common sense." In cognitive science, this difficulty falls under the heading of the *frame problem*.

We all have an idea of what it means for tasks to be simple or easy. It turns out that what is simple or easy for a human may be damned hard for another kind of cognitive system. Reaching into the refrigerator and picking out an egg is easy — if you are a human not a mechanical robotic arm. Similarly, going to the same refrigerator to make a midnight snack (to use Dennett's example) is trivial for a human but a daunting piece of decision-making for a computer. The reason is that humans have a complex set of tacit understandings and expectations — some learned, some no doubt built in — that circumscribe the decision-making problem by excluding much of what is logically possible but irrelevant[23] (Dennett 1998). People jump to conclusions and engage in other

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[23] Phenomenological approaches to human action have long understood the importance of background understandings and experience, what Schütz and Luckmann (1973, p. 99) call the "stock of knowledge." It is this stock of knowledge that allows the agent to interpret

kinds of cognitive "cheating." This allows them to solve not only problems that would be impossibly complex for an axiomatic system but even problems that are overdetermined and thus have no unique analytic solution (Pinker 1997).

Of course, Simon has also insisted that humans engage in a certain kind of cognitive "cheating." Because of the limitations of the human information-processing system, humans suffer from "bounded rationality." As a result, they must rely on *heuristics*, simplified rules that can find an approximate solution to a complex problem at a relatively lower cost of computation.[24] What has always seemed significant to me, however, is that Simon framed the notions of bounded rationality and heuristics in terms of the model of axiomatic general-purpose symbol processing (Langlois 1986). "Rationality" is bounded because it cannot reach the correct analytical solution to a complex but well-defined problem (like winning in chess). And heuristics are therefore inferior or second-best solutions. To many writers on the cognitive foundations of behavior, this formulation has its eye to the wrong end of the telescope. Far from being inferior shortcuts to a general analytical solution, the rules humans follow may in fact represent a mode of approaching complex problems *superior* to that of general-purpose

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reality. Some elements of the stock of knowledge are so fundamental that they are not merely non-conscious but are actually "a condition of every experience in the life-world and enter into the horizon of experience" (Schütz and Luckmann 1973, p. 104). Dennett (1998, p. 188) has suggested extending phenomenology into "hetero-phenomenology," which would consider the demands of action not from the perspective of what is introspectively given to humans but from the perspective of the pure information demands of action.

[24] A heuristic is "any principle or device that contributes to the reduction in the average search to solution" (Newell, Shaw, and Simon 1962, p. 85).

axiomatic symbol processing. In their seminal discussion of skills, routines, and capabilities, Nelson and Winter (1982) invoke Simon's notion of heuristics as an example of a routine. But they move quickly to locate the ideas of skill and routine more firmly in the phenomenology of Simon's intellectual opponents. Skills, in the end, are inexplicit rules connected to specific human performances. They are *tacit knowledge*, in Michael Polanyi's (1958) famous phrase.

Evolutionary psychology hints at why this is so. For many evolutionary psychologists, the physiological basis for human cognitive ability resides in the fact that the brain is the result of layers of historical evolution and thus consists not in a single central-processing unit (as in a von Neumann-style computer) but rather in a congeries of interacting organs or faculties each "designed" by evolution for a different role.[25] In computer terms, the brain is not a powerful CPU with a few simple support chips but rather a system of powerful but specialized co-processors governed by a relatively weak CPU. It is still unclear exactly how all of this works. And there is considerable controversy over what we may call the strong program of evolutionary psychology, namely, that much (most? all?) of human behavior can be explained in terms of specific hard-wired modules or faculties that evolved in specific evolutionary environments. But even researchers skeptical of the strong program are increasingly inclined to see the brain not as a pure engine of calculation but as a "layered, hybrid modern mind [that] is capable of experiencing, learning, knowing, and problem-solving, at all levels, sometimes employed at the same time, but in different ways" (Nelson and Nelson 2002, pp. 723-4).

The future of work.

The view from cognitive science informs our discussion in a number of ways. It is far from implausible, for example, to entertain the hypothesis that the evolutionary environment in which our ancestors found themselves may offer clues to the cognitive strengths and weaknesses of present-day humans as pieces of the productive system. Hunter-gatherers were clearly adaptors and creative problem solvers. They were highly skilled in the sense developed earlier: they needed to know many different routines and had the ability to switch among tasks. Surely most of the cognitive background assumptions of our ancestors's environment carry over to our own at all but the most superficial levels: objects still tend to fall down not up, etc. Thus, an information-processing system that is highly specialized and domain specific along a computational dimension becomes a general-purpose technology along an economic dimension. Human beings can do all sorts of things competently and flexibly, albeit at low rates of throughput. They are thus well suited to a wide range of tasks with similar

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[25] And, if Antonio Damasio (1994) is right, organs and systems outside of the brain proper are also part of the cognitive process — of the mind.

cognitive profiles, from driving trucks to repairing trucks to running the Teamsters Union. Humans are natural "buffers."

At another level, the view from cognitive science suggests something about machines as well. In effect, nature solves the frame problem by enlisting the division of labor. Human "common sense" arises from specialization to the contours and demands of a specific environment. Moreover, the evolution of flexible cognition is the exception not the rule (Pinker 1977, p. 154). Nature's tendency on the whole is to create *idiots-savants* not general-purpose problem solvers: lightning-fast cheetahs, bats that echolocate, birds that navigate by the stars.[26] The human brain itself may be a congeries of specialized *idiots-savants* who work together. So we as humans should not see it as odd that all we seem to be able to create are machines that do a narrow set of things well.

It makes good economic sense for machines to be *idiots-savants*, for the reasons Smith explained. Moreover, as robotics research has revealed, it is almost always cheaper to change the environment so that it demands less flexibility than it is to create an adaptation to a complex environment. If we want high throughput, we are well advised to stabilize the environment and simplify the computational demands of the task structure. If you want a personal computer built to your specifications, you can wander into your local mom-and-

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[26] In this and in earlier passages I have lapsed into the rhetorical trope of nature as designer. Of course I don't mean that literally, and the reader should take this locution as

pop computer shop, where the proprietor can no doubt be induced to order the necessary parts and put them together for you. But if you want to produce personal computers to specification at extremely high volumes and significantly lower costs, you are far better off setting up an automated production and distribution system of the sort pioneered by Dell (Kraemer and Dedrick 2001). The Dell system won't enquire about your grandchildren (unless some wag programs the website to do that), nor will it go home and fry up an egg for its son's supper. But the point is that we shouldn't want it to.

Just as the human being is a general-purpose technology precisely because of its cognitive specialization, the computer is an *idiot-savant* because of its cognitive generality. Of course, the computer is a general-purpose technology in economic terms, since it can be reprogrammed easily to take on a wide variety of specialized computational tasks (Langlois 2002). Giving a computer common sense is hard, but through software we can make computers into virtually any *idiot-savant* we choose. And that is exactly what we should want to do.

Even in the age of computers, high-throughput production is about altering the environment to reduce variation. In Ford's original version of the assembly line, everything was pre-programmed so that square pegs always appeared to match every square hole; eliminating variation meant eliminating

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incorporating by reference a wholly Darwinian account of the sort so well expounded by Richard Dawkins (1986) round pegs not just whales and bowls of petunias. This is why it was an important part of Ford's manufacturing concept that the product be identical so as to permit as high a throughput at as low a cost as possible. At least since the jacquard loom, however, batch processing has actually been able to handle certain kinds of variety rather easily. So long as variety is predictable — that is, so long as variety means a selection from a restricted set of known possibilities — machines can be taught to recognize and deal with it. To resurrect some terminology I proposed a long time ago (Langlois 1984), I will describe this as *parametric* variation — variation from within a known set mutually exclusive and collectively exhaustive possibilities. Any other kind of variation I will call *structural* variation.[27] Distinguishing among square, round, and triangular pegs is a parametric matter. Dealing with whales and bowls of petunias is a structural matter. Computers like those in the Dell production system have lowered the cost of managing parametric variation. You can choose from a wide menu of processors, memory, drives, etc.; but if it's not on the menu, you can't have it.

It is for fundamentally economic reasons, then, that we should continue to see machines crowd humans out of tasks in which computers have comparative advantage, namely tasks involving predictable, repetitive sequences of activities, including potentially complex but well structured calculations. This also implies that humans will crowd into activities in which humans have comparative

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[27] Metin Coşgel and I (1993) argue that this distinction actually tracks Frank Knight's more

advantage, namely tasks involving flexibility and adaptability, especially in the areas of problem solving and perceptual-motor activities.

In her study of how information technology has altered the organization of work, Shoshana Zuboff (1988) shows that this process has been going on for some time. Interestingly, this is especially clear in the realm of symbol-processing tasks like management and office work, where the need for judgment and buffering has long been moving up the hierarchy.

> Elements of managerial work most easily subjected to rationalization were "carved out" of the manager's activities. The foundational example of this process is the rationalization of executive work, which was accomplished by ejecting those elements that could be explicated and systematized, preserving intact the skills that comprise executive craft. It was the carving out of such elements that created the array of functions we now associate with middle management. A similar process accounts for the origins of clerical work. In each case, the most easily rationalized features of the activities at one level were carved out, pushed downward, and used to create wholly new lower-level jobs. In this process higher-level positions were not eliminated; on the contrary, they came to be seen more than ever as the depository of the organization's skills. (Zuboff 1988, p. 98.)

Although perhaps less obvious at first, change in mechanical tasks has followed a similar trajectory. The division of labor tends to make tasks more routine and therefore to "deskill" those who undertake those tasks. But, as we saw, that very routinization enables "skilled" integrative machines to displace those deskilled workers. It is such machinery (rather than to specialized humans) to which the

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famous (and widely misunderstood) distinction between risk and uncertainty.

most easily rationalized tasks are ultimately "ejected," leaving humans the more discretionary tasks of tending, maintenance, and design in which they have cognitive comparative advantage.

Both Simon (1997) and Zuboff cite a study of worker attitudes by Robert Blauner (1964) that examined four kinds of industries: crafts (printing), fordist assembly (automobiles), machine tending (textiles), and continuous-process (chemicals). As one might expect, workers found fordist assembly and machine tending less pleasant than crafts production; but not so continuous-process production. In that type of industry, mechanization had proceeded farther, and machines had taken over most of the routine activities, leaving workers the more interesting – more crafts-like – tasks of maintenance and problem solving. Blauner is right to see continuous process technology as the future of mechanization. Because of their cognitive comparative advantage, machines are likely to continue to absorb routine and well-defined tasks, thereby becoming more integrated and thus making production more continuous.

The process of crowding humans into tasks suitable for human cognition is not confined to the shop floor or the interior of the firm. Within the larger market economy, we ought to expect the same general phenomenon. Simon envisioned humans filling a variety of roles.

- Lower-level buffering workers. These would include workers in small-scale tasks requiring human hand-eye-brain coordination.

Such tasks would include routine or repetitive activities not worth automating or costly to automate. (The American system of road transport, designed for human drivers, comes to mind.)

- Maintenance workers, including those engaged in preventive maintenance. Someone has to clean up the mess when a whale or a bowl of petunias comes down the assembly line.
- Bosses. These are a kind of maintenance worker — people who deal with and plan for the non-routine. Simon notes, quite rightly, that redesign of production and mechanization is likely to lead to less need for management as "supervision."
- Designers, which includes not only designers of products and processes but also managers at the highest levels, who are designers of organizations.
- Those involved in personal-service occupations, who have to deal with the most unpredictable environment of all — other humans. Which occupations remain personal-service ones will depend, however, on which can be more cheaply redesigned to eliminate variation. In banking, automated tellers reduced the number of human tellers. But in the restaurant business, the automat of the

> 1950s failed miserably in displacing what we now refer to as the "waitperson."

Simon seems to suggest that, as automation proceeds, humans will progressively shift down this list, away from not-yet-automated assembly tasks and routine maintenance and into design, management, and personal service. Voilà the service economy, already clearly envisioned forty years ago.

Will this be a better place? Clearly this sort of analysis cannot answer a question of such weight and complexity. But it does arguably cast light on one important aspect. Even the most routine sorts of jobs into which humans are likely to be shunted — like truck drivers or hairdressers — are clearly crafts occupations in the sense described earlier. They require the operative to switch among a wide set of routines and tasks, and they present that operative with a wide variety of stimuli. This speaks directly to one of the crucial considerations in the debate about technology: the issue of cognitive narrowing that so troubled Adam Smith and many others. Indeed, the present analysis would argue strongly against any criticism of mechanization aimed fundamentally at the issues of task narrowing or deskilling.

Of course, one could always conjure up unpleasant visions of a future knowledge economy (as the service economy is now called) on other grounds. In his cyber-punk short story "The Beautiful and the Sublime," Bruce Sterling (1989) gives us a future in which the advance of automation has moved the domain of human tasks so far down Simon's list that artists and aesthetes have become the rising dominant class. This is not necessarily all to the good, if the shallow and self-absorbed narrator and his friends are meant to be representative. Or maybe Simon is right in this as well: "perhaps more of us will be salesmen" (Simon 1960, p. 38).

References.

Abernathy, William and James M. Utterback, 1978. "Patterns of Industrial Innovation," *Technology Review* (June/July).

Ames, Edward, and Nathan Rosenberg. 1965. "The Progressive Division and Specialization of Industries," *Journal of Development Studies* **1**(4): 363-383 (July).

Ashby, W. Ross. 1956.. *An Introduction to Cybernetics*. London: Chapman & Hall.

Babbage, Charles. 1835. *On the Economy of Machinery and Manufactures*. Fourth edition. London: Charles Knight.

Blauner, Robert 1964. *Alienation and Freedom*. Chicago: University of Chicago Press.

Braverman, Harry. 1974. *Labor and Monopoly Capital*. New York: Monthly Review Press.

Cosmides, Leda, and John Tooby. 1987. "From Evolution to Behavior: Evolutionary Psychology as the Missing Link," in J. Dupré, ed., *The Latest on the Best: Essays on Evolution and Optimality*. Cambridge: MIT Press, pp. 277-306.

Cosmides, Leda, and John Tooby. 1994. "Better than Rational: Evolutionary Psychology and the Invisible Hand," *American Economic Review* **84**(2): 327-332.

Damasio, Antonio R. 1994. *Descartes' Error : Emotion, Reason, and the Human Brain*. New York : G.P. Putnam,.

Dawkins, Richard. 1986. *The Blind Watchmaker*. New York: Norton.

Dennett, Daniel C. 1998. *Brainchildren*. Cambridge: MIT Press.

Donald, Merlin. 1991. *Origins of the Modern Mind*. Cambridge: Harvard University Press.

Dreyfus, Hubert L. 1979. *What Computers Can't Do: The Limits of Artificial Intelligence.* New York: Harper Colophon, revised edition.

Hounshell, David A. 1984. *From the American System to Mass Production, 1800-1932: The Development of Manufacturing Technology in the United States*. Baltimore: Johns Hopkins University Press.

Houthakker, Hendrik S. 1956. "Economics and Biology: Specialization and Speciation," *Kyklos* **9**: 181-89.

Karlsson, Fredrik. 1996. "The History of Swedish Match Manufacture." http://enterprise.shv.hb.se/~match/history.html

Knight, Frank H. 1921. *Risk, Uncertainty and Profit*. Boston: Houghton-Mifflin.

Kraemer, Kenneth, and Jason Dedrick. 2001. "Dell Computer: Using E-commerce to Support the Virtual Company," Center for Research on Information Technology and Organizations, University of California, Irvine (June).

Landes, David S. 1969. *The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present.* Cambridge: Cambridge University Press.

Langlois, Richard N. 1984. "Internal Organization in a Dynamic Context: Some Theoretical Considerations," in M. Jussawalla and H. Ebenfield, eds., *Communication and Information Economics: New Perspectives.* Amsterdam: North-Holland, pp. 23-49.

Langlois, Richard N. 1986, "Rationality, Institutions, and Explanation," in R. N. Langlois, ed., *Economics as a Process: Essays in the New Institutional Economics*. New York: Cambridge University Press.

Langlois, Richard N. 1999a. "The Coevolution of Technology and Organization in the Transition to the Factory System," in Paul L. Robertson, ed., *Authority and Control in Modern Industry.* London: Routledge, pp. 45-72.

Langlois, Richard N. 1999b. "Scale, Scope, and the Reuse of Knowledge," in Sheila C. Dow and Peter E. Earl, eds., *Economic Organization and Economic Knowledge: Essays in Honour of Brian J. Loasby.* Aldershot: Edward Elgar, pp. 239-254.

Langlois, Richard N. 2001. "Knowledge, Consumption, and Endogenous Growth," *Journal of Evolutionary Economics* **11**(1): 77-93.

Langlois, Richard N. 2002 "Digital Technology and Economic Growth: the History of Semiconductors and Computers," in Benn Steil, David Victor, and Richard R. Nelson, eds., *Technological Innovation and Economic Performance*. Princeton: Princeton University Press for the Council on Foreign Relations, pp. 265-284.

Langlois, Richard N., and Metin M. Coşgel. 1993. "Frank Knight on Risk, Uncertainty, and the Firm: A New Interpretation," *Economic Inquiry* **31:** 456-465 (July).

Langlois, Richard N., and Metin M. Coşgel. 1998. "The Organization of Consumption," in Maria Bianchi, ed., *The Active Consumer*. London: Routledge, pp. 107-121.

Leijonhufvud, Axel. 1986. "Capitalism and the Factory System," in R. N. Langlois, ed., *Economics as a Process: Essays in the New Institutional Economics*. New York: Cambridge University Press.

March, James G. 1991. "Exploration and Exploitation in Organisational Learning," *Organization Science* **2**: 1-19.

Marglin, Stephen A. 1974. "What Do Bosses Do?" *Review of Radical Political Economy* **6**: 33-60 (Summer).

Marshall, Alfred. 1961. *Principles of Economics*. Ninth (variorum) Edition, vol. I. London: Macmillan.

Marx, Karl. 1961. *Capital*. Moscow: Foreign Languages Publishing House, Volume 1.

Nelson, Katherine, and Richard R. Nelson. 2002. "On the Nature and Evolution of Human Know-how," *Research Policy* **31**: 719–733.

Nelson, Richard R., and Sidney G. Winter. 1982. *An Evolutionary Theory of Economic Change*. Cambridge: the Belknap Press of Harvard University Press.

Newell, Allen, and Herbert A. Simon. 1961. "Computer Simulation of Human Thinking," *Science* **134**: 2011-2017.

Newell, Allen, J. C. Shaw, and Herbert A. Simon. 1962. "The Problem of Creative Thinking," in H. E. Gruber, G. Terrell, and M. Wertheimer, eds., *Contemporary Approaches to Creative Thinking*. New York: Atherton Press.

Pinker, Steven. 1997. *How the Mind Works*. New York: W. W. Norton.

Polanyi, Michael. 1958. *Personal Knowledge*. Chicago: University of Chicago Press.

Pratten, Clifford F. 1980. "The Manufacture of Pins," *Journal of Economic Literature* **18**(1): 93-96.

Robertson, Paul L., and Lee J. Alston. 1992. "Technological Choice and the Organization of Work in Capitalist Firms," *Economic History Review* **45**(2): 330-49 (May).

Sabel, Charles F. 1982. *Work and Politics: the Division of Labor in Industry*. New York: Cambridge University Press.

Schütz, Alfred, and Thomas Luckmann. 1973. *The Structures of the Life-World.* Trans. R. M. Zaner and H. T. Engelhardt, Jr. Evanston, Ill.: Northwestern University Press.

Simon, Herbert A. 1960. “The Corporation: Will It Be Managed by Machines?” in M. L. Anshen and G. L. Bach, eds, *Management and the Corporations, 1985*. New York: McGraw-Hill, pp. 17–55.

Simon, Herbert A. 1962. “The Architecture of Complexity,” *Proceedings of the American Philosophical Society* **106**: 467-482.

Simon, Herbert A. 1997. “On the Alienation of Workers and Management,” in *idem*., *Models of Bounded Rationality*. Cambridge: MIT Press, Volume 3, pp. 183-196.

Smith, Adam. 1976. *An Enquiry into the Nature and Causes of the Wealth of Nations*. Glasgow edition. Oxford: Clarendon Press. [First published in 1776.]

Sterling, Bruce. 1989. “The Beautiful and the Sublime,” in *idem*., *Crystal Express*. Sauk City, WI: Arkham House.

Stewart, Doug. 1994. “Herbert Simon: Thinking Machines,” *Omni* (June). http://www.omnimag.com/archives/interviews/simon.html

Stinchcombe, Arthur L. 1990. *Information and Organizations.* Berkeley: University of California Press.

Tooby, John, and I. DeVore. 1987. “The Reconstruction of Hominid Behavioral Evolution through Strategic Modeling,” in Warren G. Kinzey, ed., *The Evolution of Human Behavior: Primate Models*. Albany : State University of New York Press.

Zuboff, Shoshana. 1988. *In the Age of the Smart Machine*. New York: Basic Books.