Useful Knowledge as an Evolving System:

the view from Economic history

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Introduction

"Knowledge" has become fashionable again. Books and articles with the word, preferably paired with "Economy" and "Growth" are coming out in droves. In his collection Essays in the Theory of Risk-Bearing, Ken Arrow used the term extensively, long before the return of knowledge to respectability. I studied these papers while in graduate school, and find myself returning to them often. They represent the kind of models that are most useful to the economic historians, who can be squarely classified as consumers rather than producers of theory. Arrow's work has inspired an entire generation of empirical economists concerned with the role of technology in the modern economy, and provided the theoretical underpinnings that inspired a great deal of the new growth economics and a great deal of the work of those economic historians – a number of them at Stanford – who realized the importance of technological change as the central feature of economic change in modern history.

What we learned from Arrow above all is that the market for knowledge does not work as well and in the same way as the markets for most other commodities. There is an inherent riskiness against which insurance cannot be obtained, and a public good property that makes it impossible to design first-best allocative mechanisms. Competitive economies will not get the production and diffusion of new knowledge quite right, no matter what. Despite an enormous amount of research, technology and knowledge have remained a slippery topic for economists.

Yet the historian needs to tell his tale. And the big story is that in the past centuries useful knowledge has become a dominant factor in History. It was not always thus: in the more remote past, economies could and did grow with only minimal and slow changes in technology. Even in the more recent past, institutional changes have contributed to the process of economic growth. All the same, it is surely true that we are richer today because we know more than past societies. The process of modern growth is different from the kind of growth experienced in Europe and the Orient before 1800 in that it is sustained. Whereas in the premodern past, growth spurts would always run into negative feedback, no such ceiling seems to have been limiting the economic expansion of the past two centuries. Even the horrors of two world wars were, in the long run, unable to slow down the expansion of those economies – primarily but not exclusively "western" – that were able to get their institutional foundations in order. At least for those, economic growth seems, to put it somewhat crudely, to have lost its concavity.

The enigma of modern growth has led to a great deal of modeling and speculation amongst economists interested in the topic. One important strand in the literature has been that the Malthusian models that provided much of the negative feedback before 1800, have been short-circuited by the desire and ability of a growing number of individuals to reduce their fertility (Galor and Weil, 2000; Lucas, 1998). Another has been institutional change, which has reduced opportunistic behavior and uncertainty. What has not been stressed enough is that the new technology was made possible by ever increasing "useful knowledge" as Kuznets called it.[1] The sources of this growth in knowledge, surprisingly, have not been fully analyzed. The "new Growth Economics" has realized that new technology is created by inputs, such as the resources devoted to R&D and investment in human capital. Although we have learned a great deal from this literature, its contribution to the understanding of the mechanism of growth of useful knowledge is tantamount to opening a black box, finding a smaller black box inside it and calling out "Eureka."

How does the kind of "useful knowledge" that Kuznets (1965) and Machlup (1982)

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[1] Kuznets (1965, p. 87). Elsewhere, he seems to have preferred the term "tested knowledge" but given the ambiguity of what constitutes an "acceptable" test, I shall refrain from using that term.

wrote about a generation ago emerge and develop? Why does it occur in one society and not another, at one time, and why does it take the form it does? There are two different approaches we can take. One is to bite the bullet and attack the highly imperfect market for knowledge despite the many difficulties is poses, and try to analyze the supply and demand for new technology.[2] The underlying assumption here is that people who discover new knowledge are in it primarily for the money, and that technology is "produced" by a rational economic system. In this model, the limits of the resources on which society can draw to produce this knowledge are not fully specified, and so the exact production function that determines the relation between the inputs and the output of new knowledge is still left in the middle. The other approach is to concentrate on the historical process of new knowledge creation and to examine the details of how new knowledge is created by various combinations of luck, trial and error, inference, and experiment. An explicit consideration of the incentives and economic mechanisms involved can be incorporated in this story, but they do not drive the outcome.

The historical route comes less natural to the economist, but it might be one worth experimenting with once more.[3] In what follows, I will define some of the terms with some more precision, and then propose an evolutionary framework to analyze them, stressing both the advantages and shortcomings of employing an evolutionary framework to the economic history of useful knowledge. The argument that an evolutionary framework is a natural way to approach the "history" of complex phenomena seems to be enjoying a renewed popularity, although many of the applications of "evolution" to the history of useful knowledge use rather

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[2] This approach characterizes the research that economic historians have carried out in the traditions established by Zvi Griliches. See for example Khan and Sokoloff, 1998, 2001

[3] The work of Richard Nelson, starting with Nelson and Winter (1982) and culminating in Nelson (2000a, 2000b) and Nelson and Nelson (2001) has inspired much of what is to follow.

informal and at times careless formulations (e.g. Basalla, 1988).

Useful Knowledge

Technology and production are about harnessing natural phenomena and regularities for our material welfare. It seems therefore natural to define useful knowledge in those terms, and leave out other forms of knowledge such as social forms of knowledge such as economic, legal, social, and institutional knowledge. The confusion implied by this terminological choice is minor: some of the "useful" knowledge here is really not applicable directly to production, whereas organizational knowledge or familiarity with institutions are, of course, of great importance. There are obvious gray areas such as psychology. But when we ask questions about technology in the strict sense above, this shortcut may be acceptable.

A number of remarks on the meaning of the concept of useful knowledge thus defined follow:

1. The useful knowledge of a society is defined as the union of the knowledge of the individuals in that society and whatever is stored in storage devices. Density can then be defined as the ratio of the size of shared knowledge (weighted by the number of people sharing it) to total knowledge.
2. The knowledge set is partitioned into two subsets which are distinct. One is propositional or S-knowledge which describes and catalogues natural phenomena and the relationships between them. The other is prescriptive or 8-knowledge which contains instructions that can be executed.[4]

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[4] The partitioning of useful knowledge in this way is commonly carried out by epistemologists (Scheffler, 1965). Michael Polanyi (1962, p. 175) points out that the differences boils down to observing that S can be "right or wrong" whereas "action can only be successful or unsuccessful." He also notes that the distinction is recognized by patent law which will patent inventions (additions to 8) but not discoveries (additions to S), though some new techniques, of course, are not patentable. In some way, the dichotomy between S and 8 is symmetric to Ryle's (1949, see also Loasby, 1996) distinction between knowledge "that" and knowledge "how."

3. Propositional knowledge S contains what we today would call "science" (formalized knowledge) but it contains a great deal more, including geographical knowledge, artisanal and agricultural knowledge, and any other natural regularity and phenomenon that can be exploited in some way.[5] Some fields of knowledge, such as "engineering science" and "applied mechanics" are somewhere between science and artisanal knowledge (Rosenberg, 2001).

4. Prescriptive knowledge 8 consists of a monstrous book of blueprints, whether codified or tacit, of techniques that society could carry out if it wanted. Only a small proportion of those techniques are actually ever executed. Each element of 8 consists of a set of instructions, much like a recipe. These recipes can be codified as they are in cookbooks or engineering manuals, or they can be implicit and tacit.

5. Each technique in 8 has an epistemic base or support in S. This base contains the knowledge of the natural regularities that are harnessed for this technique to be possible, and can be wide or narrow. The wider it is, the more that is understood about how and why the technique works. The size of the base is bounded from below by a degenerate support: the very least a society must know about a technique is that it works (the catalog of 8 is part of S). If nothing else is known, we may call these "singleton techniques" (because their epistemic base consists of one element). For each technique we can describe a minimum epistemic base without which it could not exist. As the epistemic base widens, society knows more about the natural processes at work, which has major implications about the rate of technological progress. The epistemic base is

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[5] Examples include an intuitive grasp of the "six engines" of classical antiquity (the lever, wheel, wedge, screw, pulley, and balance), as well as the lubricating qualities of oil, the direction of the trade winds, the response of crops to fertilizers, and that the offspring of two animals with some salient characteristic was more likely to display this characteristic.

not bound from above, because we can always know "more" about the natural processes at work around us.

6. The width of the epistemic base determines the ability of an economy to improve upon an existing technique, extend its applications, economize its production process, and adapt it to new circumstances. Inventions based on narrow epistemic bases have low adaptability and tend to lead to technological stasis fairly soon after their emergence.

7. There is no requirement for the epistemic base of any technique used historically to be "true." Indeed, "true" can only mean here "conforms to the S-knowledge of 2001." Considerable chunks of past technology were used – with some success – based on elements of S we no longer accept, such as Ptolemaic astronomy. As long as it can serve as the basis for some kind of action, "knowledge" here really is "believing."

8. Knowledge can, however, be defined as "tight" or "untight." Tightness has two dimensions: confidence and consensus. The tighter a piece of knowledge is, the stronger the belief people have that a piece of knowledge is true, and the less likely it is that many people hold views inconsistent with it. Flat Earth Society members and those who believe that AIDS can be transmitted by mosquito bites may be few in numbers, but many Americans still do not believe in the Darwinian theory of evolution and believe in the possibility of predicting human affairs from looking at the stars.

9. There is a historically important connection between the tightness of S-knowledge and that of 8-knowledge. Tightness of S depends on persuasion and on rhetorical conventions (such as mathematical proof, the interpretation of experimental and statistical data, and the confidence in experts and authorities), but the tightness of techniques is often readily verified if the efficacy of the technique is readily observable.

However, in those techniques in which the efficacy of the technique is hard to verify (or may have unintended side-effects), its tightness will be higher, the tighter the knowledge that serves as its epistemic base. Conversely, if a technique based on an untight piece of S knowledge can be shown to work, this success will increase confidence in the S-knowledge supporting it.

10. Knowledge is distributed and shared, that is, individuals specialize in what they know. Access to knowledge possessed by others is therefore an important variable determining the technological capabilities of a society. Access costs are the costs paid by a person acquiring knowledge from a source, and depend on the technology, institutions, and culture of knowledge transfer. For instance, the invention of the printing press, the emergence of "open science" in the seventeenth century, and the development of "search engines" such as technical encyclopedias and manuals in the eighteenth are examples of access-cost-reducing developments.
11. There is an important difference between an epistemic base, the propositional knowledge necessary to make an "invention" (i.e., write a new "program"contained in 8) and the knowledge needed to execute these instructions by a firm or household activating the technique, a concept often referred to in the business literature as "competence." Normally, it is not possible to write a complete set of instructions. They are written in code, and the codebook itself is tacit, or the code to decipher the codebook is, and so on (Cowan and Foray, 1997). Often many of the codifiable instructions are not included either. The relation between competence and epistemic base is quite complex.

An Evolutionary approach to Useful Knowledge

The notion that useful knowledge evolves over time in a manner in some ways analogous to phylogenetic processes has been suggested many times. The idea goes back to the 1950s through the work of Karl Popper and Donald Campbell and has ripened into a field now known as evolutionary epistemology.[6] Originally, the notion was to apply Darwinian models of "blind variation cum selective retention" to science, but the analogies with technology were too obvious to be ignored and were soon made explicit in the work of historians of technology such as Edward Constant (1980), Walter Vincenti (1990), Brian Cragg (1989), George Basalla (1988), and John Ziman (2000). Applying a methodology from one field to another in a mad scramble for isomorphisms, shoehorning concepts into uses for which they were not intended seems a bad research strategy. If we are to find any use for an evolutionary approach to the history of useful knowledge, it needs to develop its own framework. Evolutionary theory as a mode of historical explanation is larger than biology.

It is striking, however, to what extent the analogy with technology and machines has been attractive to biologists and natural scientists. What has prompted the analogy is not only the fanciful notion that the difference between a machine and a living being is one of degree (Mazlish, 1993), but because many biologists and systems theorists have noted that the evolutionary dynamics of living beings is similar to that of technology.[7] In what follows, I will try to demonstrate that something can be learned from this analogy, but that the differences between Darwinian systems and systems of knowledge are as instructive. Models of cultural evolution such as Cavalli-Sforza and Feldman (1981, see also Cavalli-Sforza, 1986) and Boyd

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[6] For surveys, see Wuketits, 1990; Bradie, 1986; Hahlweg and Hooker, 1989.

[7] Examples include biologists (Stebbins, 1982, p. 432; Vermeij, 1995, p. 144; Mayr, 1988, p. 259; Vogel, 1998, pp. 298f) as well as complexity theorists (such as Cohen and Stewart, p. 330 and Kauffman, p. 202) have been sympathetic to an analogy between natural history and technological history,

and Richerson (1985) pursue this question in much greater detail and deal with a wider array of cultural phenomena. Here I will try to focus on "useful knowledge" and technology only.

Central to any evolutionary approach to knowledge is the choice of the unit of analysis. The difficulty in isolating the correct unit of knowledge or culture has derailed much of Richard Dawkins's idea of "memes" as an analog of genes. The ill-chosen use of the artefact has derailed much of George Basalla's (1988) otherwise pioneering attempt to provide a coherent "evolutionary theory" of technology. On the other hand, choosing epistemic units of selection such as "ideas" also has run into considerable doubt. Despite recent attempts to revive "memetics" as a serious science, the definition of the "unit" remains the Achilles heel of the Dawkinsian program (Kuper, 2000; Bloch, 2000; Boyd and Richerson, 2000). I propose to overcome this difficulty by taking the Nelson-Winter concept of the technique as the fundamental "unit" of technology. Each element of 8 is a separate and bounded unit or recipe, containing a set of instructions how to produce a good or service. Such a definition has its share of ambiguities, but it is immune to the objections launched against "memes."[8] Although techniques are obviously related to other techniques in similar ways that different species are (as complements, rivals, parasites, or unrelated), they can be meaningfully distinguished from one another. A technique, not unlike a living specimen is "alive" when it is executed.

An evolutionary model consists of three components: structure, dynamics and heritability, and variation-cum-selection.[9] The odd thing is that for a model to be "evolutionary,"

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[8] The most serious of these objections is that there is no guarantee that ideas or "memes" are replicated identically from mind to mind even if they generate the same phenotypical performance because language and other mediating tools come in between (Boyd and Richerson, 2000, p. 155). Lists of instructions on how to produce, however, can in principle be codified, and although some component of it remains tacit and is thus vulnerable to the same critique, the teaching process creates built-in incentive to replicate the content accurately.

[9] This classification differs a bit from the classic tripartite definitions suggested by Lewontin (1970) and Maynard Smith (1986).

there is no absolute need for it to evolve (in the more common use of the term), that is, to change constantly over time. One can imagine an evolutionary system that for all practical purposes has reached a stationary state in which all innovations are suppressed and in which the environment is constant. Such a system would not be an interesting one to study (except perhaps in order to examine the evolutionary process that led to a dead end), but it would be evolutionary.

Structure. An "evolutionary" framework of the type that will prove useful here rests on the distinction between an underlying basis that constrains but does not wholly determine a unit that is the manifested entity. This duality is not part of the classical Darwinian set-up. But modern Darwinism is unthinkable without Mendel, and what Mendelian genetics added to Darwinian theory was the distinction between the appearance and traits of a unit of analysis, and the underlying information that brings this "phenotype" about and is shared with other, similar entities. Evolutionary systems are systems of information and some of that information "does something" and creates a "manifest entity." In biology, the underlying structure is the genotype consisting of DNA and the manifested entity is the living specimen, that is, the phenotype. There is a mapping from genotype to phenotype, and while it is not wholly determinate, it is easy to see how the genotype constrains what the phenotype cannot be. A giraffe is limited by its genes from looking like a hippopotamus. In the history of knowledge, these classes correspond – very roughly – to our earlier distinction between propositional knowledge and prescriptive knowledge. The distinction between information ("knowing") and applying it ("doing") seems useful in a world of technology. Propositional knowledge cannot rule in any techniques, but it can rule out a lot. Societies that do not have advanced physics are constrained away from building nuclear reactors or MRI machines. All the same, the underlying epistemic base does not determine the exact shape of the technique, and a lot is left to the environment (taken widely as consisting not only of the physical and institutional parameters, but also relative prices, factor costs, and the existence of other techniques, whether substitutes or complements).

A great deal of the "underlying" knowledge is inactive or "dormant": the vast majority of all useful propositional knowledge is non-coding or "junk" in the sense that it does not apply directly to production. Perhaps some dormant segments of useful knowledge, such as advances in paleontology or improved understanding about the distances of other galaxies or the properties of black holes are at first glance dormant forever, but many dormant sections of S can become active given a change in the environment.[10]

It is important to realize the limitations of this correspondence. The minimum epistemic base of many techniques, as noted, can be quite slender or even close to a singleton. When such techniques emerge, often by accident or by arduous processes of trial-and-error, they are limited in their expandability and adaptability. [11] It is the overall narrowness of the epistemic bases of pre-1800 techniques that imposed the concavity of technological progress functions. Their expansion after 1800 is the subject of a forthcoming book (Mokyr, 2002) and this is not the place to discuss them. There is no equivalent to the variable width of the epistemic base in

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[10] Most scientific (let alone other forms of) knowledge has no applications and does not affect production technology right away although it may be "stored" and in rare cases called into action when there is a change in the environment or when another complementary invention comes along. By "environment" here, I mean not only the physical environment in which the technique operates but also the development of complementary or rival techniques which may lead to the activation of previously dormant knowledge. Indeed, such processes are what constitutes "adaptation" in all evolutionary processes.

[11] Vincenti's (1990) use of Laudan's (1984) framework of the selection and solution of technological problems, akin to Landes's notion of "challenge and response," followed by choice between rival solutions, provides one way to look at the connection between knowledge and technique; the knowledge provides the tools to solve the problem, while the technique embodies the solution. Other mechanisms can be imagined. There are very few limitations on the knowledge underlying a technique: it can vary from the list provided by Vincenti (ranging from "fundamental design concepts and operational principle" to "design instrumentalities") to pure personal experience ("I tried it and it works, but I don't know how").

evolutionary biology: a trait either has a base in the DNA, in which case it might exist, or it does not. Yet does that invalidate an evolutionary approach? It could be argued that the fairly narrow parameters of evolutionary biology are a special case, and that cultural evolution can be and usually is far more flexible than that of living beings.

The existence of a minimum epistemic base is a necessary condition for a technique to emerge, but it does not describe anything like a sufficient condition. A great deal of technological history happens inside the envelope of propositional knowledge: some simple mechanical devices such as the wheelbarrow or barbed wire were perfectly feasible long before they emerged, but it stands to reason that they did not emerge earlier because they did not occur to anyone. Even when the ideas are there, there could be a variety of technical and institutional barriers to the emergence of the new element in 8, and even more barriers in its actual execution.

There is another widely discussed difference between Darwinian biology and the evolution of useful knowledge. Whereas the genetic base of a species is entirely embedded in the DNA of a living specimen and vanishes as soon as the species goes extinct, underlying useful knowledge can survive even if the techniques it implies are no longer in use. In other words, in all living beings the composition of the gene pool depends on the selection of the phenotypes because the genes cannot exist outside the living beings which are the "vehicles" or "carriers" of the genetic information. In this respect, useful knowledge is quite different because, unlike DNA information, it is exosomatic, that is, it can be stored in storage devices – primarily human minds who can retain knowledge of a technique even if they do not execute it. Indeed, a technique can in some sense be "extinct" (not used by anyone) and yet still survive in 8 (e.g., explained in old engineering textbooks or history of technology articles or survive embodied in an artefact). All the same, the analogy has some merit because the tacit component of knowledge is irretrievably lost unless a way is found to codify and store it. It is also conceivable (although I cannot think of a historical instance) that the epistemic base that has supported a technique vanishes but the technique itself survives. The connection between S and 8 is thus different from that of that between genotype and phenotype, and they co-evolve in dynamic patterns that could become quite complex. The set-up of this structure is illustrated in fig. 1.

Dynamics. Evolutionary models are historical in the sense that they are designed to explain existing outcomes on the basis of their past. The historical element that provides evolution in living beings with its inertia is heritability. Evolutionary units need to replicate. Each living specimen's genotype is a linear combination of his parents' genotypes plus a small error term (a mutation).[12] It was once believed that such error could be fairly large and create "hopeful monsters," but the evidence for the viability of such radical departures is weak (Charlesworth and Templeton, 1982). Similarly, in the history of useful knowledge, innovation is predominantly "local" and thus constrained by history because it is limited by the cumulative knowledge of the past. This inertia holds equally true for S and 8 knowledge: both have an internal dynamic in which change is made possible by cumulative past change, which produces

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[12] It seems plausible, for instance, to think of it as a Markov Chain in which the state in t is dependent entirely on the state in t-1 plus some transition probabilities, and earlier history does not matter since it is entirely encapsulated in the state at t. "Extinction" might then be thought of as an absorbing barrier, but as long as the underlying knowledge (or some crucial component of it) has not been lost, the technique can be regenerated.

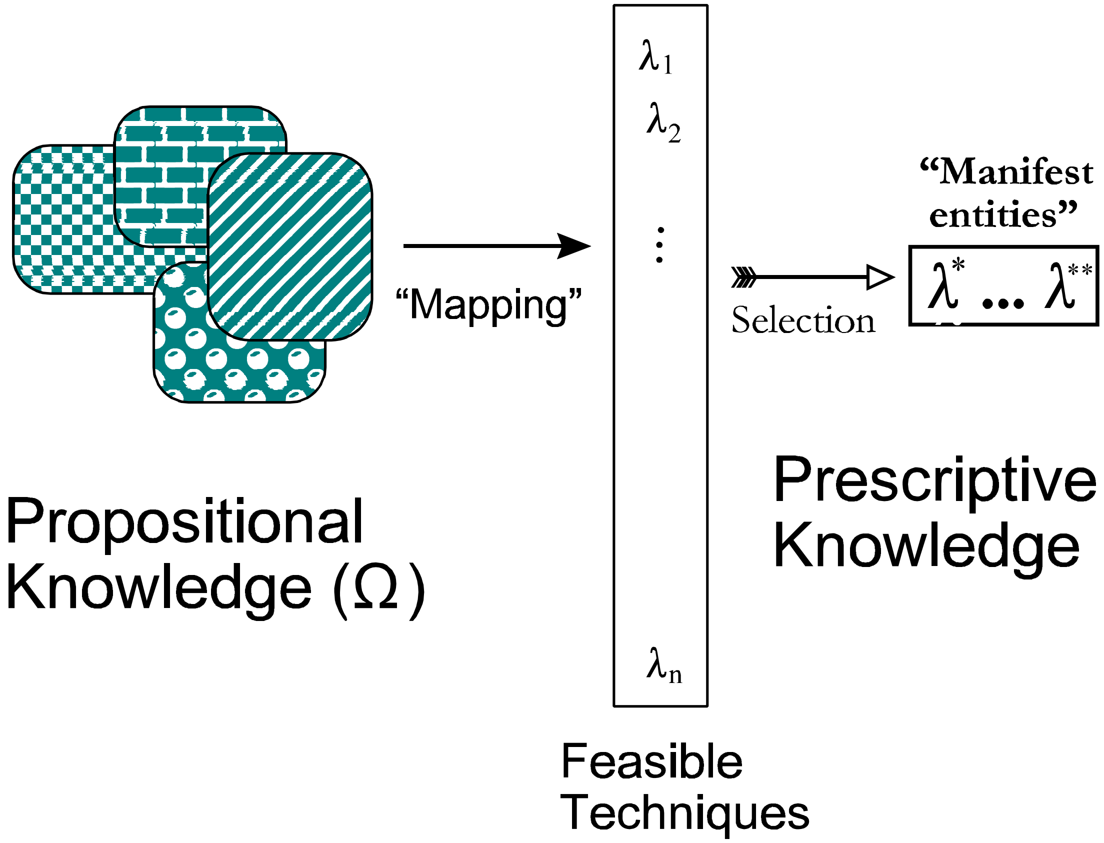
λ_1
λ_2
⋮
λ_n
"Mapping"
Selection
"Manifest entities"
$\lambda^* \ldots \lambda^{**}$
Propositional Knowledge (Ω)
Prescriptive Knowledge
Feasible Techniques

Figure 1

both the challenges and the opportunities for further progress. While there is no a priori limitation on how large an innovation can be, and some radical departures (macroinventions) can be discerned, they are rare. The vast bulk of accretions to useful knowledge are small and local.

What makes biology evolutionary is that the carriers of genetic information are subject to wear and tear and have finite lives, so they have to transmit this information over time through reproduction. During reproduction, the potential for germ-line change is released, either through linear combinations with existing information (in the case of biparental reproduction) or through mutation. In models of cultural evolution the transmission over time works different. The underlying propositional knowledge, as noted, can exist and evolve on its own without being "expressed" in an underlying technique.[13] Propositional knowledge is "expressed" by the techniques it generates, and its manifest entity is observable when the prescriptive knowledge is actually carried out.

How and why do techniques "replicate?" It might well be that the set of instructions that tell a farmer how to grow wheat on a field "reproduces" when he carries out the same instructions the next year, but unlike Samuel Butler's famous chicken, which was nothing but the way for an egg to make another egg, techniques require people to reproduce. Reproduction can take place in two ways: intrinsic and extrinsic reproduction. Normally reproduction simply takes place through human memory: if you know how drive a truck from Chicago to Des Moines today, you can do it again next week. The successful long-term reproduction of a

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[13] The underlying structure of technological phenotypes lives and reproduces independently of the living specimen. If a particular understanding of physics in S (say, water starts boiling when heated) maps into a technique (say, here is how you prepare a cup of tea), that knowledge will be passed on and reproduce itself whether tea is drunk in this society or not. The selfish or unselfish "gene" of knowledge does not need its carrier – though the carrier needs the gene. It is still true, however, that when a child is taught to make a cup of tea, the implicit knowledge that water boils when heated is "carried" in these instructions, so the child does not have to know about water boiling. The argument I am making is dependent on the notion that "heated water will boil" and "how to make tea" are different kinds of knowledge, but the difference is not on the order of "an elephant" and "the genes that make an elephant."

technique, however, requires an extrinsic mode of transmission between humans such as imitation or training. The concept of a "generation" is clearly arbitrary here -- though the same can be said of many forms of life: is the cutting made from a perennial plant a separate entity or the same specimen? Of course, much of what biologists do (such as taxonomy) seems less useful to the historian of technology, since phylogenetic lineages have no obvious analog in the evolution of useful knowledge (or better put, their complexity is such that such trees are not a very useful tool). None of these differences, as Cavalli-Sforza and Feldman (1981, p. 14) stress, should stop us from observing the selection and acceptance of a trait over time and the evolution of the distribution of the frequency of a technique in the population.

Evolutionary processes are both inertial and path-dependent. No species can change too much at one time, though neither biologists nor cultural evolutionists will agree easily on how much "too much" is. Given enough time, however, small differences can be bifurcating and lead to quite different outcomes in the long run. Path dependence means that final outcome depends on the exact itinerary taken, (David, 1994, 1996, 1997). This implies that there is a great deal of contingency in determining the final outcome of the historical process (Mokyr, 2001b). Consider two disjoint environments that develop separate trajectories. Some fairly minor difference far back in history could determine whether mammals would develop as marsupials or placentals, and unless these environments came into direct contact, their histories could remain different. There was nothing inevitable about the appearance of zebras or cockroaches, although there are certain morphological traits such as wings and eyes that have appeared more than once independently and can therefore be said to have some kind of evolutionary logic. Evolutionary logic, moreover, rules out a large number of imaginable life forms that violate some obvious constraint. All the same, the evolutionary logic cannot be extended to declare some observed outcomes as "inexorable." There certain was nothing ex ante inevitable about the appearance of intelligent life on this planet, although it may not be quite as much of a fluke as Stephen Jay Gould supposes (Wright, 2000).

Something similar could be argued for the development of technology. It is an interesting question is whether modern technology as it evolved in the past two centuries can be assessed as dictated by some kind of evolutionary logic (Mokyr, 2001). The answer depends on whether we take the epistemic base as given: given an S set, the likelihood of a particular set of techniques evolving is fairly high, even if the particular form it takes is of course still up for grabs. But how "probable" were the components of propositional knowledge that supported modern technology themselves to emerge? And how probable were the institutions and meta-rules which supported the emergence of this S-knowledge?

Selection. Natural selection is the key to any evolutionary model. Given superfecundity and variability, selection can impart adaptive properties on the units of evolution. As has long been realized, cultural selection of any kind does not work exclusively through the mechanics of differential survival and reproduction of specimens or "memes," but through conscious decisions made by agents. Fitness, in the sense of a likelihood of being selected, is still a meaningful concept, however, and much of the story to be told in technological selection does mirror our notions of natural selection. But again, literal adherence to the biological model can be misleading: in the living world, selection occurs on phenotypes, the living specimens. Whether "selfish genes" manipulate the organisms or not, the selection process on the organisms determines whether the underlying information structure survives or not. If the organisms survive and reproduce, the DNA they carry is "retained." If they do not, and the species goes extinct, both genotype and phenotype are gone.

In the evolution of useful knowledge, there is a dual process of selection which is considerably more complex. We need to consider separately the selection on prescriptive knowledge and propositional knowledge. Technological selection on 8-knowledge is relatively straightforward. Evolutionary logic dictates that for selection to occur, there has to be variability among entities. In the world of technology, variability and diversity are ubiquitous. History, geography, and culture have conspired to create a enormous deal of technological variability. So have human creativity and human folly. For instance, there are many ways to drive from Cincinnati to Kansas City and among those certain specific routes are selected and others are not. One would conjecture that drivers would settle on the shortest, fastest, or cheapest route, but the outcome will depend on what the agent knows and likes, as well as on road conditions that could change. We can be reasonably sure, all the same, that the chosen route does not lead through Philadelphia. Many of these choices on techniques are trivial, of course, and the area above the isoquant is not very interesting. After a choice has been made and a technique has been executed, the outcome is evaluated by a set of selection criteria that determine whether this particular technique will be actually used again or not, in a manner comparable to the way in which natural selection criteria picks living specimens and "decides" which will be selected for survival and reproduction and thus continue to exist in the gene pool.

Here "tightness" is central to the story. Some techniques are tight, in the sense that we can evaluate their characteristics easily. Choosing between a dot-matrix and a laser printer, or between surgery with or without anesthesia is a no-brainer. But in many cases firms and households have difficulty evaluating the effects of techniques, and fitness becomes to some extent contingent. In a few documentable cases, techniques that were ineffective (as it seems to us) were selected and retained, to a point that still baffles historians.[14] Economists tend to think of a selection environment consistent with rationality (even if techniques are untight) but it is clear that historically selection is influenced by other factors such as politics, aesthetics, and ideology, and hence fitness itself is highly contingent on a large number of variables.[15] All the same, choices are made, and some techniques are retained for selection, others are not.

Selection on S-knowledge is more complex. As noted, unlike what happens in living beings, the retention of the underlying information is not a by-product of the survival of the "manifest entities." There is no "selfish knowledge." Unlike techniques, which are "selected" when they are being "used" by someone, it is more ambiguous what it means for a unit of S to being "selected". To be included in S at all, a piece of useful knowledge must be in existence either in someone's mind or a storage device from which it can be retrieved. It is therefore unclear what precisely would be meant by superfecundity unless there is some physical constraint about the amount of knowledge that society can carry as a whole. Only if there is some form of congestion of knowledge or storage cost will society shed some pieces of knowledge as it acquires and selects better ones. Through most of human history before the Age of the Gigabyte, such congestion was a reality: books were hugely expensive before the invention of printing, and while their price fell with the advent of printing, they were still quite costly by the time of the Industrial Revolution. Other forms of storage outside human memory banks such as drawings, models, and artefacts in musea, were all expensive. Some selection may

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[14] Hall (2001), for instance, poses the difficulty that artillery in the early modern period employed guns in which the aspect ratio (the ratio between length and calibre) was far larger than optimal, and that the "cannon" (a piece of artillery of approximately optimal aspect ratio) took centuries to become dominant despite the rather obvious way in which the optimal ratio could be measured through experimental methods.

[15] Contingency can be compounded when selection is frequency-dependent so that prior choices become a factor in fitness. In technical selection this occurs not only in the widely discussed cases of network externalities, but also when techniques are untight and agents engage in imitation as an information-cost saving device.

therefore have even occurred at that level. But when storage costs fell, congestion became less of a problem, and thus the issue of selection became moot. Libraries are full of old science and engineering books, as well as books on alchemy, astrology, quack medicine and other forms of superseded knowledge about the regularities of the natural world, and the knowledge in them can be retrieved whether their manifest entities are expressed or not. Yet in our own time, the improved ability to store knowledge is matched by the growth in our capacity to generate new knowledge, and even now we must dispose of some knowledge that seems redundant -- so selections are made. Perhaps the concept of selection which, at its most abstract level has a binary interpretation (either a unit is selected or it is not) should be replaced by a continuous variable of accessibility, measured by the costs of finding and retrieving knowledge that has been preserved. This variable would become infinite for knowledge that has been permanently disposed of.

Evolutionary epistemology has suggested a different definition: Selection may be viewed as the process in which some people choose to believe certain theories and regularities about natural phenomena and reject others. Yet this interpretation of selection on S-knowledge is also problematic. For one thing, it is not identical to the previous definition. While of course certain views of nature are incompatible with each other so that some theories are rejected if others are accepted, the discarded theories and beliefs do not necessarily become extinct in the technical sense of being inaccessible. Thus the humoral theory of disease is still understood today, but no longer serves as a source for prescriptive techniques in modern medicine. Scientific theories that are "accepted" will normally be the ones that are mapped onto the techniques in use, whereas the ones that are rejected will be dormant, known only to historians of knowledge or stored in library books. Accepting the work of Lavoisier meant that one had to abandon phlogiston theory but not necessarily destroy any trace of it.

Moreover, here, too, selection may not mean a binary variable of either accepting or rejecting a piece of knowledge. Untight knowledge means, basically, that a person may have a subjective probability distribution on whether the knowledge is "true." What matters here is whether a person will "act" on that knowledge, that is, whether he or she will select a technique based on knowledge that is untight. Some people may plausibly swallow large amounts of Vitamin C on the basis of the untight belief that ascorbic acid strengthens the immune system. Rational choice implies that the person will select technique depending on the cost functions associated with type I and type II errors. It is quite possible, in other words, to "select" a technique even if the preponderance of the evidence is that the epistemic base on which it rests is false, much like a technological Pascal's wager.

The stringency of the selective pressures could also vary. A high-pressure intellectual environment forces choices between incompatible views. In a low-pressure intellectual environment many "species" of S-knowledge could coexist in one mind even if by some logical standard they were mutually inconsistent. People might believe that even if there are natural laws, they could somehow generate exceptions (such as magic or miracles). The selection criteria in S are culturally contingent, and it is easy to envisage a cultural climate in which the question "but is it true?" can be routinely answered by "sometimes" or "maybe" or "if God wills it."[16] Furthermore, the selection criterion "is it true?" might have to compete with such criteria as "is it elegant?" or "is it morally improving?" or "is it consistent with our traditions?" Science, to be sure, is largely consensual, and glaring inconsistencies with observed facts are frowned

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[16] An example is the Jain belief of *syadvada*, which can be summarized to say that "the world of appearances may or may not be real, or both may and may not be real, or may be indescribable, or may be real and indescribable, or unreal and indescribable, or in the end may be real *and* unreal *and* indescribable." Cited by Kaplan (1999) , p. 45, emph. added.

upon. People have to choose between incompatible or incommensurate theories and will do so if they can, in some sense, rank them (Durlauf, 1997).

Selection of propositional knowledge by this definition is determined by the rhetorical conventions accepted in society that persuade people that something is "true" or at least "tested." Such rhetorical conventions vary from "Aristotle said" to "the experiment demonstrates" to "the estimated coefficient is 2.3 times its standard error." These standards are invariably socially set within paradigms: what constitutes logical "proof"? what is the acceptable power of a statistical test? do we always insist on double blindness when testing a new compound? how many times need an experiment be replicated before the consensus deems it sound?

Much of the tightness of knowledge is a function of social relations such as "who is an authority" on a subject, who appoints those authorities, and how often do non-experts question authority. If a piece of knowledge is not very tight, as Durlauf shows, choosing between competing pieces of knowledge may well become a function of imitation, persuasion, and fashion.[17] How and why such choices take place is of course the central issue in the History of Science with opinions varying between scholars to what extent evolutionary success is correlated with some measure of "progress" or "truth" (Hull, 1988; Kitcher, 1993).

There is one other dynamic element that differs – in a degree – between biological and technological selection systems. In living systems, the selection process is myopic: the dynamic properties that the investigator discerns ex post are not observed by the system; selection takes

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[17] One example to illustrate this principle: A Scottish physician by the name of John Brown (1735-88) revolutionized the medicine of his age with Brownianism, a system which postulated that all diseases were the result of over- or underexcitement of the neuromuscular system by the environment. Brown was no enthusiast for bleeding, and instead treated all his patients with mixtures of opium, alcohol, and highly seasoned foods. His popularity was international: Benjamin Rush brought his system to America, and in 1802 his controversial views elicited a riot among medical students in Göttingen, requiring troops to quell it. A medical revolutionary in an age of radical changes, his influence is a good example of the difficulty which contemporaries had selecting amongst alternative techniques and the enormous possibilities for failure in this area (Brown was asserted to have killed more people than the French Revolution and the Napoleonic Wars combined).

place exclusively by the criteria of present fitness, not using the criterion of the fitness implications of the future development implied by the choice made. This myopia can of course lead to disastrous long-term consequences.[18] In technological systems, because the choices are made by intelligent forward-looking agents rather than by the mechanical processes of survival and reproductive success, it is conceivable that selection is not wholly myopic but may instead select (or reject) a technique for its future potential rather than its immediate consequences. Such assessment of the future are, however, very hazardous to make and people can and will differ about the dangers of slippery technological slopes. Yet much of the current debates on techniques such as genetically modified organisms or nuclear power must be understood in this way.

Evolution and the Economic history of Technology

What lessons can economic historians learn from such an evolutionary story and how can they best apply it? First and foremost, it suggests that they have been ignoring the history of science and technology at their peril. The dual structure of the model suggests that the intellectual origins of technological progress are not peripheral to the enterprise but at the very basis of it. What has confused scholars, in my view, is that they have taken too narrow a view of "science" as a proxy for what I have called S-knowledge. Such an approach inevitably truncates what really might have mattered: an accumulation of pragmatic knowledge on mundane natural regularities and better access to it, which both increased the epistemic base of techniques and increased the likelihood of projecting from that base onto the set of techniques.

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[18] Selection could misfire when a trait leads to what Allen and Lesser (1991) call "positive feedback traps," that is, selection of a trait because of its success in satisfying the fitness criterion but trapping it at a low level. Their example is the peacock's tail, which helps each peacock in the reproductive game and thus conveys a selective advantage despite the uselessness of the tail in survival-related functions. The same was true for the extinct Irish Elk: its enormous antlers gave its bearers a putative advantage in mating, but they were apparently useless as a defensive tool, and helped in the demise of the species.

The practical knowledge collected by engineers like John Smeaton, ironmasters like Darby and Cort, potters like Josiah Wedgwood, or clockmakers like John Harrison was, in the early stages of the Industrial Revolution, economically more valuable than the science of Cavendish, Lavoisier, or Dalton.

Invention in a world of very narrow epistemic bases, could be thought of it much like a random mutation in a purely Weismannian world of undirected innovations. Invention in such a world is serendipitous or the result of inefficient and clumsy trial and error processes. When it occurs, the likelihood of much further progress is low. This is not to say that there are no systematic differences between different societies in their rates of technological change, much as there are differences between environments in their mutagenicity. But the inventions that occur and the needs of society are largely uncorrelated. The only mechanism that gives it direction is the selection on 8. Such a process could provide technological progress over a long period, but techniques would be limited by their narrow epistemic bases.

To be more exact, imagine a parameter D which measures the correlation between the probability of an invention occurring and the "needs" of the system. In a purely Darwinian system D = 0; mutations are undirected, and the directionality of the system is imparted entirely by selection. In such a world technological change is not produced by directed research and development but purely by serendipity, and much of the modern theory of endogenous growth does not apply. No historical system in which D was zero ever quite existed, but before 1750 in most areas it was quite close to it. Change was produced by "tinkering," and nature, too, is often regarded as making changes that way (Jacob, 1977).

The other extreme possibility, equally imaginary, is a world in which D = 1, and the system produces whatever knowledge it needs through R&D. In such a world, technological knowledge is just another commodity, which is produced in the system through a production function. In such a world, techniques are not free (since knowledge is costly to produce) but there is no explicit constraint on what new knowledge is or is not feasible. As the epistemic base became wider after 1800, D increased and the process of invention became more directed, the searches more efficient, and the likelihood of expanding and adapting a technique to changing circumstances became more likely. Yet the serendipitous and accidental component in invention remained high even if it declined a bit over time.

The higher the level of D, the more we can speak of technological change as being "induced," that is, sensitive to signals that the economy sends (Ruttan, 2000). Yet it is also clear that inducement here can mean different things. First, responses to exogenous stimuli can be built into the software of a technique in the form of conditional instructions. This flexibility is comparable to what biologists call "phenotypic plasticity," or what Williams (1966) has called a "facultative response" ("if x then do y"). Second, society can search over its entire catalog of 8's and replace techniques in use by others when there is a change in the environment. This is simple substitution, and comes closest conceptually to the adaptive nature of natural selection. Third, at a higher level we can find what biologists refer to as "genetic assimilation" (a term due to Conrad Waddington).[19] The idea is that the activation of existing genetic information is sensitive to environmental stimuli, and natural selection favors organisms in which the activation of "dormant" information is feasible. One can imagine a world in which an external shock, from a change in relative prices to a natural disaster, will cause society to search over its existing S-set looking for existing knowledge that will form the basis of a new technique that

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[19] Waddington argued that mutations are predominantly "neutral" and do not affect the selection criterion one way or another, but may become useful when the environment changes and calls for adaptation (see also Stebbins, 1982, p. 76).

has now become attractive. This phenomenon is closest to induced invention. Fourth, society can channel its research agenda to expand those segments of S that are more likely to map eventually into a technique it desires, so that not only the technique is induced but also the S-knowledge on which it rests. While these four mechanisms differ in detail, they all point to the fact that wider epistemic bases of techniques in use mean higher adaptability and flexibility both for the techniques in use and indirectly for the people using them.

Evolutionary dynamics of this kind can help us understand some crucial aspect of economic history. The co-evolution of the S-set (what people knew) and the 8-set (what they did) in the later eighteenth and early nineteenth centuries in Europe produced a positive feedback loop that ignited a chain of technological innovations we often refer to as the Industrial Revolution and which eventually led to the emergence of modern economic growth. In the terms used by system theorists, there was a state transition, and technology went from a state in which negative feedback dominated to one of positive feedback producing what Kaufmann has called a "supercritical" state. Instead of eventually burning itself out and asymptoting away, as it had done in the past, technological progress continued apace and embarked on a trajectory in which it eventually spun out of control. The continuous back and forth interaction between propositional and prescriptive knowledge created what Geerat Vermeij (1987, 1994) has called "escalation." By its very nature, this divergence phenomenon was not an economy-wide phenomenon: it differed in degree and in timing from industry to industry and from technique to technique. During the first Industrial Revolution it was confined to a few sectors, and its impact on the aggregate economy was not decisive. But as the epistemic base was built up, by the growth of science, engineering, and the accumulation of a growing base of empirical knowledge about "what worked," coupled to declining access costs, the phase transition took place in the decades between 1815 and 1860.

Both of these mechanisms provide an explicit way in which the two types of knowledge interact in a positive feedback relation, creating a co-evolutionary dynamic in which all bets are off. Much like genotype and phenotype, S and 8 inhabit different "geographies." When this happens, and the attractors in S and 8 do not "match up" nicely, feedback can have a creative effect and both parts of the structure can change in unpredictable ways (Cohen and Stewart, 1994, pp. 420-21). The interaction between S and 8 is something economic historians can readily trace, even if data here takes the form of "anecdotes."

The feedback from 8 back to S is of course very different in nature than the feedback from phenotype to genotype which (according to the Weismannian orthodoxy) cannot occur within a single organism and depends on populational processes that alter relative gene frequencies. In the context here, escalation is created by the processes by which techniques enhance the S knowledge base on which they rest, which creates ever better techniques and so forth. This works through a number of mechanisms. One of these is Rosenberg's (1976) famous concept of "focusing devices." When a technique is known to work, but nobody is quite sure why and how it does so, the puzzle will stimulate and focus the attention of scientists or natural philosophers on the subject, in part out of pure curiosity, and in part out of a desire to adapt and extend the technique further.[20] The second is Derek Price's (1984) idea of "artificial revelation." Price argued that science (and for that matter all knowledge of natural phenomena) is far more constrained by the technology of observation, measurement, and processing than is commonly realized, and that a great deal of progress in propositional knowledge was due to the emergence

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[20] The infusion of practical knowledge about industry into academic research in the electric industry became sufficiently important for one historian (König, 1996) to suggest that we could term what emerged "industry-based-science" as much as "science-based-industry."

of certain instruments and tools that simply extended our ability to watch, experiment, and compute. A relatively minor invention (advance in 8) may set off a new area of useful knowledge that eventually led to large-scale technological advances. Finally, techniques may help to tighten propositional knowledge: research tools and instruments have in the past succeeded in confirming or refuting conjectured regularities; once this knowledge was sufficiently tight, it made more sense to spend resources in looking for techniques based on it.

Knowledge and technological change after 1750

The "phase transition" that occurred in the technological universe of the West after 1750 thus depended on a mutual relationship between S and 8. Historians have not emphasized this enough, in part because they have tended to look only at formal science which was a small (if rapidly growing) subset of S. A few examples below drive this home. Consider first the well-documented and understood case of steampower. One might consider the minimum epistemic base of an atmospheric engine to be the realization that the surface of the earth is really at the bottom of an atmospheric ocean. This knowledge emerged when Evangelista Torricelli invented the barometer in the 1640s, leading to widespread attempts to measure atmospheric pressure, the most famous of which were Pascal's experiments at the Puy de Dôme. Many people began wondering how this pressure could be exploited, among them the great Dutch physicist and mathematician Christiaan Huygens and the Englishman Robert Hooke. A model of a steam engine was first constructed by Denis Papin (a student and protegé of Huygens's) and the real thing followed in the form of Thomas Newcomen's famous 1712 Dudley Castle engine. The improvements introduced by Smeaton, Watt, Trevithick, Woolf, and others in the late eighteenth century relied mostly on empirical extensions of this knowledge basis, and while they improved the engine, its efficiency was constrained by their failure to understand the basic laws that regulated that efficiency.[21] The "scientific part" of the epistemic base was inspired by the engine, and expanded a great deal between 1824 and 1850, as physicists in France, Britain, and Germany worked out the fundamental laws they called thermodynamics.[22] This epistemic base led in its turn to fundamental improvements in the utilization of steam power when William Rankine made the insights of thermodynamics available to engineers (Channell, 1982).[23] Once these laws were understood, it became clearer how to design internal combustion engines. In 1876 N.A. Otto filed a patent for an internal combustion engine based on the four-stroke principle. Without the constant growth of the epistemic base, the steam engine would have ended up like another source of energy like water- and wind power, raising productivity for a while, but eventually running into diminishing returns. To be sure, no simple linear progression should be imagined here.[24] Yet it is striking that in the following decades, the engine invented by the eponymous Rudolf Diesel was designed in the light of thermodynamic principles, trying

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[21] As late as the 1830s, the understanding of steam power was still as a vapor-pressure engine rather than a heat engine. The influential engineering books by Farey (published in 1827) and François-Marie Pambour (1837), were still based on the standard assumption of steam in this way. See Woolrich (2000) and Kroes (1992).

[22] The first enunciation of the principles at work here – efficiency was a function of the differences in temperature – were laid out by a French engineer, Sadi Carnot, in 1824 after observing the differences in efficiency between a high pressure Woolf engine and an older model. The next big step was made by an Englishman, James P. Joule who showed the conversion rates from work to heat and back. Joule's work and that of Carnot were then reconciled by a German, R.J.E. Clausius [the discoverer of entropy], and by 1850 a new branch of science dubbed by William Thomson (later Lord Kelvin) "thermodynamics" had emerged (Cardwell, 1971, 1994).

[23] Rankine, the author of *Manual of the Steam Engine* (1859), made thermodynamics accessible to engineers and Scottish steam engines made good use of the Carnot principle that the efficiency of a steam engine depends on the temperature range over which the engine operates. His study of the unresolved issues of the effects of expansion led to his recommendation to apply steam-jacketing to heat the cylinder (a technique previously tried but then abandoned). One of Rankine's students, John Elder, developed the two-cylinder compound marine engine in the 1850s, which sealed the eventual victory of steam over sailing ships.

[24] N.A. Otto insisted that he was unaware of the paper written a few years earlier by Alphonse Beau de Rochas, which proved theoretically that the Carnot principles applied to all heat engines, and that the most efficient system would be a four-stroke cycle.

to maximize fuel efficiency.[25]

The history of chemicals before 1900 shows a similar image of a gradually widening epistemic base interacting with technology. Most of the breakthroughs before the "chemical revolution" were largely serendipitous, and relative to the hopes that many had in the early eighteenth century regarding the potential of "chemical philosophy" to produce a high return in agriculture and industry, the results before the late 1780s were disappointing (Golinski, 1992). A number of breakthroughs took place (Leblanc's soda making process of 1787 and Berthollet's discovery of chlorine bleaching), but without the corresponding changes in S, this movement would have leveled off. The chemical revolution of Lavoisier and Dalton relied in part the refinement of chemical laboratory technology in the second half of the eighteenth century.[26] A few years after the new chemistry was "announced" by the publication of Lavoisier's landmark Traité élementaire de Chimie (1789), Alessandro Volta invented his famous "pile" or battery, which was to have dramatic effects on the growth of chemistry. Volta's battery was soon produced in industrial quantities by William Cruickshank. Electrolysis became the tool by which chemists led by Humphry Davy and Michael Faraday filled in the gaps in the contours outlined by Lavoisier, isolating and discovering elements. The effects on industry were already noticeable before the advance of organic industry in the 1830s. In the 1820s the French chemist

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[25] Diesel built his engine based on the idea that the temperature of air inside a combustion chamber could be raised sufficiently by compression to ignite the fuel, thus converting all of the energy from combustion into work. He was not a "tinkerer," however, but a trained engineer, working with state of the art scientific techniques. He started off searching for an engine incorporating the theoretical Carnot cycle, in which maximum efficiency is obtained by isothermal expansion so that no energy is wasted, and a cheap, crude fuel can be used to boot (originally Diesel used coal dust in his engines). Isothermal expansion turned out to be impossible, and the central feature of Diesel engines today has remained compression-induced combustion, which Diesel had at first considered to be incidental (Bryant, 1969).

[26] Much of the late eighteenth-century chemical revolution was made possible by new instruments such as Volta's eudiometer, a glass container with two electrodes intended to measure the content of air, used by Cavendish to show the nature of water as a compound. The famous "Memoir on Heat" co-authored by Lavoisier and Laplace was made possible by the calorimeter, designed by Laplace who was, in addition to his mathematical skills, was an expert in the design of experimental instruments (Poirier, 1998, pp. 136-137).

Michel Eugène Chevreul became interested in the nature of fatty acids and isolated such substances as cholesterol, glycerol, and stearic acid. He discovered that fats are combinations of glycerol and fatty acids, easily separated by saponification (hydrolysis), which immediately improved the manufacture of soap.[27] A few decades later came the development of soil chemistry, a classic instance of the widening of the epistemic base of an existing technique, which led to the fine tuning of fertilization and eventually to the development of chemical fertilizers.

Mineral exploration provides another example of the positive feedback between S- and 8-knowledge. The Industrial Revolution was not the beginning of the widespread use of coal in Britain, and much of the growth of the Tudor and Stuart economies can be attributed to the adoption of coal as the fuel of choice in manufacturing.[28] Yet throughout the eighteenth century mining entrepreneurs were, in Flinn's words, forced to rely on surface observation and folklore (Flinn, 1984, p. 40). William Smith's association with Somerset coalminers focused his attention on the basic issue in geology namely that it had to be knowledge in three dimensions and that he needed a key to understanding the strata. This key was supplied by his insight that geological strata could be identified by the fossils found in them, and that collecting enough data would make a geological map possible. Decades of collecting this information yielded Smith's "Map that Changed the World" (Winchester, 2001), one of the more palpable increments in the S-set

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[27] Clow and Clow in their classic account (1952, p. 126) assess that his work "placed soap-making on a sure quantitative basis and technics was placed under one of its greatest debts to chemistry." His better understanding of fatty substances led to the development of stearic candles, which he patented in 1825 together with another French chemist, Gay-Lussac. His work on dyes and the optical nature of colors was also of substantial importance.

[28] In his excellent survey of the issue, John Harris (1988) points out that the switch from charcoal to coal-based fuels in the iron industry in the second half of the eighteenth century is often believed to be the first such transition whereas in fact it was "virtually the last." Industries such as soapboiling, brewing, and glassmaking had switched to coal centuries earlier, and home-heating (the largest use for fuel) had become dependent on coal much earlier as well.

during the Industrial Revolution.[29] Smith became a valuable consultant to mineowners and geology increasingly informed the search for minerals. After that, geology can be seen to co-evolve with the techniques of exploration, although it took many decades to become fully integrated with it. The widening epistemic base of mineral exploration and mining technology surely were the reason that the many warnings that Britain was exhausting its coal supplies turned out to be false alarms. From the late eighteenth century, too, boring techniques were improved and became a highly skilled craft performed by specialists In other areas related to mining, too, propositional knowledge in mining aided and abetted the actual techniques. In 1815, Humphry Davy, the most prominent scientist in Britain in his time, invented the famous "miner's friend," a lamp that minimized the chances for explosions due to exposure to open flames.

A good example of Derek Price's principle of artificial revelation is the development of the microscope. The invention of the modern compound microscope by Joseph J. Lister (father of the famous surgeon) in 1830 serves as another good example. Lister was an amateur optician, whose revolutionary method of grinding lenses greatly improved image resolution by eliminating chromatic and spherical aberrations. The invention was used to construct a theoretical basis for combining lenses and reduced average image distortion by a huge proportion, from 19 to 3 percent. Lister was the first human being ever to see a red blood cell (Reiser, 1978). His invention changed microscopy from an amusing diversion to a serious scientific endeavor and eventually allowed Pasteur, Koch and their disciples to refute spontaneous generation and to establish the germ theory, one of the most revolutionary changes in useful knowledge in human history and mapped into a large number of new techniques in medicine, both

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[29] The geological map, produced in 1815, was 8' by 6', hand-painted and showed the "delineation of the strata" in Britain, with the "collieries and mines" – clearly this knowledge was meant to be exploited.

preventive and clinical. Another example of techniques aiding in scientific discovery is the spill-over from the synthetic chemical industry to the growing understanding of cell biology through the technique of staining pioneered by the young Paul Ehrlich in the 1880s (Travis, 1989).

Bacteriology and chemistry depended on formal science, but most of the interesting action was in the less formal segment of S. Much of the advance in textiles, pottery, glass, paper, clock- and instrument making, and food processing depended on minor discoveries on how to manipulate materials and machines. In metallurgy the interaction between the non-science part of S knowledge and techniques played a major role in some of the great break-throughs of the era. The epochal invention of the Industrial Revolution was Cort's puddling and rolling technique (1785), which owed little to formal metallurgy or chemistry but a great deal to pragmatic knowledge about natural phenomena.[30] Cort realized full-well the importance of turning pig iron into wrought or bar iron by removing what contemporaries thought of as "plumbago" (a term taken from phlogiston theory and equivalent to a substance we would call today carbon). The problem was to generate enough heat to keep the molten iron liquid and to prevent it from crystallizing before all the carbon had been removed. Cort knew that reverberating furnaces using coke generated higher temperatures. He also realized that by rolling the hot metal between grooved rollers, its composition would become more homogenous. How and why he mapped this prior knowledge into his famous invention will never be exactly known, but the fact that so many other ironmasters were following similar tracks indicates that they were all drawing from a common knowledge pool.

Two generations later, the Bessemer steelmaking process of 1856 was invented by a man

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[30] See Hall (1978, p. 101); in a famous letter, Joseph Black wrote to James Watt that Cort was "a plain Englishman, without Science."

who, by his own admission had "very limited knowledge of iron metallurgy" (Carr and Taplin, p. 19). His knowledge was limited to the point where the typical Bessemer blast, in his own words was "a revelation to me, as I had in no way anticipated such results." Yet the epistemic base was by no means empty: Bessemer knew enough chemistry to recognize eventually that the reason why his process succeeded and similar experiments by others had failed was that the pig iron he had used was, by accident, singularly free of phosphorus and that by adding carbon at the right time, he would get the correct mixture of carbon and iron, that is, steel. He did not know enough, however, to come up with a technique that would rid iron of the phosphorus; this took another twenty years, when the basic process was discovered. The epistemic base at the time was, however, larger than Bessemer's knowledge. This is demonstrated by the recognition, by an experienced metallurgist named Robert Mushet, that Bessemer steel suffered from excess oxygen, which could be remedied by the addition of a decarburizer consisting of a mixture of manganese, carbon, and iron. The Bessemer and related micro-inventions led, in the words of Donald Cardwell (1994, p. 292) to "the establishment of metallurgy as a study on the border of science and technology" – the arrow of causation clearly going from 8 to S.

Conclusions

The idea of useful knowledge as an evolving entity should be not juxtaposed with knowledge as an economic entity. The two concepts are not at odds with one another but are different ways to look at the same phenomenon. Evolutionary models, however, produce somewhat different insights. One of these, which I discussed above, is that the co-evolution of S and 8 knowledge can produce a better way of looking at the technological "take-off" of the past two centuries as a mutually re-inforcing positive feedback effect and a liberation from the homeostatic constraints of the more remote past in which technology was never able to raise economic performance in a sustained way.

Such models, however, raise other issues as well, none of which can be dealt with here. One of them was pointed out by Ziman (2000): selectionist models stress that what matters to history is that very rare events get amplified and ultimately determine the outcome. The challenge to historians then becomes to try to understand which rare events take on that function, and under what circumstances they get "selected." But this way of thinking does perhaps help to remind us that us that in the emergence of useful knowledge and modern technology, a small number of persons made crucially important contributions. This is not a plea to return to the nineteenth century "hero" model of invention. Had Galileo or Newton or Planck never been born, their insights would in all likelihood have been generated by colleagues. But this knowledge was created by a small, mechanically and technically-minded elite. The culture, the institutions, the incentives, the research agendas, and the instruments at the disposal of these "vital few" were only slightly less contingent. So was the existence of mechanics, craftsmen, and engineers who could carry out their instructions, read their blueprints, and provide the parts and materials they specified with sufficient precision. The idea of a tiny but crucial sliver of the labor force driving history by adding materially to the useful knowledge that the rest of the workers were relying upon seems apposite. In 1666, Robert Hooke noted that the newfound world of making inquiries in "the nature and causes of things" in order to produce something of use for themselves or mankind, must be conquered "by a Cortesian army, well-Disciplined and regulated, though their numbers be but small."

No more than for biology can this kind of thinking yield exact predictions or even very good explanations. In fact, the indeterminacy of history through layers of contingency is a reminder that, whatever the differences between phylogenetic development and the history of technological change, both imply that whatever happened did not have to happen. What we can do at best is to show how whatever did not happen mostly could not have happened. Historical explanation is thus advised that some modicum of modesty is apposite, and that attempts to make "the rise of the West" seem natural or inevitable or even overdetermined are much like attempts to explain the emergence of intelligent life on the planet. There was nothing ineluctable about it, much less can we explain why it happened when it did. Homo sapiens could not have evolved before the cretaceous extinction of the dinosaurs, but there is no reason why it could not have happened in the middle of the tertiary, for instance, during the period known as Oligocene. An evolutionary perspective reminds us of a truism that too much neoclassical belief might obscure: "Very few things happen at the right time, and the rest do not happen at all."[31]

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[31] The statement is from Mark Twain's "acknowledgements" to *A Horse's Tale* and attributed to him – in jest – to Herodotus. He adds mischievously that "The conscientious historian will correct these defects."

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