Science, Technology, and Knowledge:
What Economic Historians can learn
from an Evolutionary Approach.

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Introduction

How are we to think of the *fundamental* causes of technological change? Although economists in the past decade have made major advances in trying to account for the appearance of modern economic growth in the West and its subsequent diffusion to other parts of the world, their work has not yet been found to be uniformly satisfactory among other social scientists or even their own colleagues.[1] Instead of criticizing standard analysis again, I propose to explore an alternative. Sustained economic growth depends crucially on the growth in human knowledge, both in terms of *what* is known and *who* does the knowing (Mokyr, 2002). What is needed, then, is a historically-informed framework to analyze useful knowledge. What follows is an attempt to create a framework for an evolutionary approach to the economic history of technological change. The idea that knowledge can be analyzed using an evolutionary epistemology based on blind variation and selective retention was proposed first by Donald Campbell and has since been restated by a number of scholars in a wide variety of disciplines.[2]

A reasonable criticism of such arguments has been that whereas models of blind-variation with selective retention may be an instructive way to look at innovations, they add little direct insight that cannot be gained from standard models. Many insights about innovation come more naturally from evolutionary models, although most such results can also be teased from standard models, properly specified. For instance, economics' knee-jerk response is to regard technological diversity as a source of inefficiency: if an identical product under very similar circumstances is made in very different ways, our first suspicion as economists is that at least one of the producers is doing something wrong. An evolutionary perspective, on the other hand, tends to regard variability as a possible source of innovation and long-run successful performance.[3]

[1]The most ambitious of these attempts is clearly Galor (2011), but see also for example Clark (2007). An excellent summary of much of the recent literature is Helpman (2004). For critical reviews see Vries (2013) and McCloskey (2010).

[2]The original statement was made in Campbell, 1987. Among the most powerful elaborations are Hull, 1988 and Richards, 1987. For a cogent statement defending the use of this framework in the analysis of technology see especially Vincenti, 1990 and more recently Aldrich et al., 2008.

[3]Alfred Marshall, who always had a weakness for evolutionary models, noted that "the tendency to variation is a chief cause of progress" (Marshall [1890] 1920, p. 355). Cf. Raffaelli (2003). For a similar argument, see Allen, 1988, esp. pp. 107-08.

Moreover, by some standards we could define the biological processes as "wasteful" without much evidence that mechanisms that make the use of scarce resources more efficiently will eventually be eliminated (Wesson, 1991, p. 94).

Part of the confusion in the use of Darwinian models in the economics of knowledge and technology comes from imprecision regarding the unit of analysis. Arguably the unit is a matter of judgment, with the choices ranging from the gene to the group, including the individual, the nation, the group and so on. The unit I am interested here is not a living being, but an epistemological one, the *technique*. The technique is a "cultural element," something that is *known* and is shared by a subset of the population and is learned, not genetically transmitted. As such, it can be analyzed with the tools that cultural evolution has suggested to us in the seminal work by Cavalli-Sforza and Feldman (1981), and Boyd and Richerson (1985; 2005).[4] It is part of *prescriptive* knowledge (knowledge "how") as opposed to propositional knowledge (knowledge "what") — a distinction I shall come back to below.[5]

In its bare essentials the technique is nothing but a recipe or a set of instructions, a set of do-loops and if-then statements (often nested) that describe how to manipulate and harness nature for our benefit, that is to say, for production widely defined. Focusing on a *technique* underlines the main interest of students of the history of technology. Much of economics (and of Darwinian Biology) is written as a story of the struggle for survival and reproduction between competing members of a single species or the emergence of cooperation between them (Bowles, 2004; Bowles and Gintis, 2011). But the interesting action in technology is not only people competing against each other but struggling to better control their natural environment. Techniques are thus tools to play *a game against nature* and to produce a "material culture" from an unyielding and often niggardly environment. As such, the techniques themselves can be seen as it were to compete against each other to be used by people who choose among them. Below, I will first lay out the groundwork for an evolutionary analysis of technological knowledge, and briefly examine how such knowledge changes (or does not) over time.

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[4]More recent work in this tradition includes Richerson and Boyd (2005); Jablonka and Lamb (2005); McElreath and Henrich (2007); Henrich (2009); Mesoudi (2012).

[5]The papers collected in Richerson and Christiansen (2013), especially Mesoudi et al (2013), Boyd, Richerson and Henrich (2013), and Shennan (2013) provide excellent surveys of the state of the art in the area of the application of models of cultural evolution to the growth and dissemination of useful knowledge.

A few definitions.

To start off, we need a definition of what essential elements constitute a Darwinian model. It will surely come as no surprise that there is little consensus on the matter amongst biologists or evolutionary theorists on the matter. Darwinian models encompass a larger set than just the evolution of living beings and population dynamics whence it first originated (Aldrich et al., 2008). Darwin himself recognized the applicability of random variation with selective retention to changes in language.[6] The biological reproduction of living things in this scheme of things turns out to be a rather special case of a broad set of such dynamic models. The main idea of a Darwinian model is a system of self-reproducing units that changes over time. A Darwinian model must contain three fundamental elements, that were already fully realized by Darwin; some of the other elements of modern genetics such as the Weismannian barrier and the randomness of mutations do not carry over (Aldrich et al., 2008; Hodgson and Knudsen, 2010, p. 35-36; Mesoudi, 2012). How, then, should we think about a Darwinian cultural model that can help us understand technological change?

First, any Darwinian model must be a dynamic system of change over time, a stochastic process of some definable characteristics that are transmitted over time. The way this happens in biology is through reproduction, and the cultural equivalent of the process is socialization: beliefs, preferences, and values are transmitted from parents (and others involved in socialization) to children. Economists have began to explore various aspects of this process and examined its implications for the evolution of culture (Bisin and Verdier, 2011). In this kind of a model techniques "reproduce" from period to period and thus "carry" the knowledge embodied in them over time. A technique, in this view, uses human agents to reproduce itself to make another technique much like, as in Samuel Butler's famous quip, a chicken is the way an egg produces another egg. Through most of history, the replication process took place in the context of the master-apprentice

[6]Douglass North (1990) has suggested a similar approach to the development of economic institutions, Richard Dawkins (1976) to the realm of ideas ("memes"), Cavalli-Sforza and Feldman (1981), and Boyd and Richerson (1985) to culture, Donald Elliot (1985) to the analysis of Law, and Daniel Dennett (1995) to practically everything.

relationship, which has recently been the subject of much research and debate in economic history. The horizontal replication of techniques (and other cultural variants) involves *imitation* or *persuasion*.[7]

Beyond just absorbing the knowledge and beliefs of others, however, people have new ideas, and thus innovation enters the system (Witt, 2009). Innovations need not be random: as Nelson (1995) has stressed, these models are in a class that is more or less half-way between deterministic and purely random dynamic systems, what he calls "somewhat random variation." These innovations create internal variation that defines the options for the system to move to.

Again, the evolutionary dynamics differ in important ways between living beings and any kind of knowledge. In living beings, persistent change occurs only through gene mutation (essentially random change) and direction occurs through selection on the living beings which carry them. In knowledge systems there are two stochastic process at work. First, propositional knowledge reproduces itself over time through learning with possible "mutations" (discoveries about natural phenomena and regularities). Second, the techniques that form part of prescriptive knowledge also reproduce themselves and there, too, there can be change, say, through experience and learning by doing. The two stochastic processes are clearly related, with feedback going in both directions. Such feedbacks do *not* occur in living beings, where Lamarckian feedback mechanisms from phenotype to genotype are ruled out.

A second characteristic is that cultures, much like species, contain a great variation of traits. Variability is key to the selection process, by definition.[8] Cultural variability is the result of past innovations. Over time, a vast number of cultural traits have accumulated, and many of these traits are shared among certain groups of individuals and distinguish them from those belonging to other groups. Yet the lines are often blurry, as they are between species, and overlaps are common. Jews and Muslims share a belief in a single God and a taboo on the eating of pork, yet they are quite distinct groups in a way not dissimilar from two species that share the vast bulk of their genes yet are phenotypically quite distinct. The set of techniques

[7]Aldrich et al., 2008, p. 587 argue that the concept of "replicator" differs from "diffusion," as replication involves adding "developmental dispositions and capacities" that add complexity. For my present purposes, however, the distinction is unnecessary.

[8]As argued in Aldrich et al., (2008, p. 582) all complex population systems can be analyzed in terms of general Darwinian principles. The systems considered here involve populations of entities. Populations are defined by members of a type that are similar in key respects, but within each type there is some degree of variation, due to past innovation and historical contingency.

known to society— a subset of the set of all cultural variants — falls directly under the definition of the sum of all past innovations. But other variants are equally interesting to the economic historian, such as attitudes and beliefs that affect the accumulation of human capital, the willingness to defer gratification ("patience capital" in the terminology of Doepke and Zilibotti, 2008), or attitudes to work vs leisure. The period 1500-1700 marks a period of feverish innovation in these cultural variants even if it was not quite as prolific in terms of inventions as the subsequent centuries.

Third, there is a property of superfecundity in the system, that is, there are more entities than can be accommodated, so there must be some selection in the system. In biology, what drives evolution is superfecundity: species have the capability to reproduce at a rate much faster than is needed for replacement, and this means that not all those who *can* be born will be, or that all those born will actually survive and reproduce. This is the Darwinian "struggle for existence." Natural selection is driven by a process in which those with the most fit features have a better chance to survive and reproduce. Cultural features are "superfecund" (perhaps "superabundant" would be a better term) in that there are far too many of them produced for an individual to absorb, so that selection must take place amongst sometimes enormous menus. There are 10,000 distinct religions in the world, and 6,800 different languages. No individual can believe in all religions and speak all languages. One has to choose. This selection process is what provides the entire system with its historical direction by determining the likelihood that a certain technique will be actually used. The nature of superfecundity in epistemological systems is different than in Darwinian biology, where entities reproduce at a rate that is faster than can be accommodated by available resources. More often than not, superfecundity means that one has to choose: no person can believe simultaneously in the Copernican and the Ptolemaic cosmological systems any more than one can be an adherent of Milton Friedman and Mao at the same time. In many other cases, however, new information is piled on top of old information, and by accepting it as valid one does not have to make a choice. In this regard the superfecundity feature of the evolutionary model is a constraint that is not invariably binding.

In the world of technology superfecundity essentially means that there are far more conceivable ways to skin a cat than there are cats and more ways to drive from i to j than can be accommodated. Selection at the level of technique in use is thus essential. However, this is far more relevant to process innovation than to product innovation: if a new and better way of making steel or curing malaria is discovered, the old technique would (in most cases) be phased out and replaced by the new one. New products, however, could take their place besides existing ones. All the same, superfecundity means selection. There are many scores of breakfast cereals on the store shelves, but households choose just a few.

As Nelson has pointed out (1995, p. 55), the theory's power depends on its ability to specify what precisely these selection criteria are. The — somewhat unsatisfactory — answer must be that they are historically contingent. How, for instance, does an economy pick the right technique from an array of options? Some societies such as nineteenth century (and to some extent modern) America emphasized price and efficiency above all, others (such as France) selected against mass production and preferred individually manufactured custom made products wherever possible. Some nations chose to generate electricity with nuclear reactors, while others stayed with fossil fuels. Unlike Darwinian models, however, selection is not a metaphor for an invisible hand kind of mechanism that operates in a decentralized and unconscious manner of mindless replicators with differential reproduction: there are actually conscious units, firms, households, and authorities that do the selecting.[9] Rather than the unit of selection, then, in this kind of model economic agents are the *selectors* themselves.

The importance of selection is critical to Darwinian models because, as noted, selection lends direction to the historical purpose of change. Selection and innovation are indispensable parts of the historical process. Without innovation, selection occurs on existing entities only, and whatever variation exists at any time will eventually crystallize or disappear altogether.

Darwinian models of technology need therefore to specify the exact mode of selection that is operating on the choice set. But because innovation consists of more or less local variation on *existing* states of the world, past selections govern the range of variability on which selection can occur, yielding the path-dependent or persistence property of these models.[10] A multiplicity of conceivable outcomes, with the actual result often determined by historical contingency, is thus part and parcel of the process. Yet it is not quite

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[9]It should be noted that the combination of selection and the particular dynamic structure defined before imply that selection is "myopic" even when it is perfectly rational conditional on what is known at the time. That is, a particular choice may seem rational but that choice places the system on a trajectory that eventually leads to less desirable outcomes. For more details, see Mokyr, 1992.

[10]By the standard definition of path dependence, this means that the final outcome depends both on the special characteristics of each technique and the historical path which partially is contingent (David, 1997).

the same as the standard problems that occur in economics with multiple equilibria and the need to refine them. As Witt (1997a) points out, the process of evolutionary change is *unending*, that is, unforeseeable mutations always can and do occur to destabilize an existing state of the world. Such mutations occur either in a given technique itself or in other techniques that are complementary or rivalrous, thus changing the environment faced by this mutation. Such a description seems to fit the world of knowledge as well as any.

Evolutionary Models and the economic history of technology

What does an evolutionary approach bring to the study of culture in general and technology in particular? For the economic historian, the great advantage of evolutionary thinking is that it tries to explain why the present is the way it is and not some other way from history. It encourages us to look on how the past shaped the present using Darwinian concepts, above all the concepts of choice and selection, and how such choices are made from past choices and innovations. Evolutionary thinking does not provide us with a clean and ready-to-use methodology like standard economics which depends on simple rules such as profit maximization, but for historical analysis of innovation it has certain merits. Above all, it stresses the importance of History: the set of techniques at each point in time is what was passed on from the past plus whatever they add or modify: a classic example of descent with variation. Some techniques are radically changed from what the past had, but even today most are not (Edgerton, 2007). Below I list some of the main advantages of an evolutionary approach to the history of culture, of which technological knowledge is a subset.[11]

First, evolutionary systems are characterized by a fundamental *duality* between information and action, between what in biology is thought of as genotype and phenotype and in a more generalized version as replicator and interactor (Hodgson and Knudsen, 2010, p. 24). Distinctions between genotype and phenotype are hazardous to extend to cultural history, but all the same, it seems, something can be learned. Culture is about matters of the mind — beliefs and preferences; behavior and actions are the observable outcomes of preferences and knowledge. But there is no easy mapping from genes to phenotypes and the mapping from beliefs to behavior is not simpler; at best there are loose statistical associations masking the

[11]Some of the following is adapted from Mokyr (2016).

interaction of many variables.[12] One reason is that beliefs, much like other genotypical processes, affect "adjacent" beliefs. We can indeed speak of technological *pleiotropy*, much like in evolutionary processes. Pleiotropy means that a certain genotypic change leads to more than one phenotypical effect, because of the spillover effects on genes in the proximity of the mutation, in a sort of genetic packaging. In some extreme cases, certain techniques spill over to a large number of uses, which is now known as General Purpose Technologies. A parallel phenomenon is *epistasis* in which more than one piece of information is required to jointly bring about a certain trait or behavior: To get a working bicycle, what is needed is not just a working transmission chain but also pneumatic tires.

Second, evolution is about the interaction between a pre-existing environment (in which an innovation is introduced) and the innovation itself. Innovation remains a stochastic variable, even if it is in some sense directed and not purely random (as mutations are supposed to be in a pure Weismannian world). We do not know precisely why a certain idea occurs to an individual at a particular time, and why in some societies certain ideas simply never occurred at all. The likelihood of an idea occurring to anyone is affected by the environment and perceived needs.[13] But even if the flow of innovations were wholly predictable, we would not be able to predict with any certainty their success unless we could measure with some precision their "fitness" relative to the environment in which they take place, which determines whether they will "catch on." What makes matters even more complicated, of course, is that even if it were possible somehow to predict the likelihood of an innovation succeeding in a given environment, that success is likely to produce complicated feedback effects because it is likely to change the environment itself.

Third, as noted above, evolutionary systems are based on the dynamics produced by superfecundity and selection. The system throws up more variants than it can possibly accommodate, and so some form of winnowing must take place. Like species, some ideas may go "extinct" in the face of a powerful new

[12]A good example can once again be found in the history of technology in the relation between propositional and prescriptive knowledge. There is no easy mapping between the two (Mokyr, 2002) and two-way feedback creates for complex dynamics. There are times when techniques are used with virtually no understanding of why and how they work. At other times, the necessary underlying knowledge may well be there, but the techniques fail to emerge — such as the absence of eyeglasses in the Greek and Roman world.

[13]An example of such directed searches is the alleged search for labor-saving innovations in high-wage economies, which supposedly explains the occurrence of the Industrial Revolution in eighteenth century Britain (Allen, 2009). For a critique, see Kelly, Mokyr and Ó Gráda (2014).

competitor (e.g., geocentric astronomy or miasma theories of disease), although extinction may still mean that the *knowledge* of a technique survives, just its use has ceased. We could still make water clocks and sundials, but their role in time measurement is non-existent. It is possible for knowledge to go completely extinct (that is, completely forgotten and lost), but the conditions for that are rather stringent and unlikely to be met today. "Extinction" might then be thought of as an absorbing barrier. However, as long as the underlying knowledge (or some crucial component of it) has not been lost, the technique can be regenerated much like the imagined preservation of dinosaur DNA in a drop of amber in *Jurassic Park*. In other cases new techniques may coexist with the old ones in some kind of mixed equilibrium in which the competitive environment is insufficiently stringent to bring about a complete domination of the innovation, or in which the two techniques occupy slightly different niches. As I shall argue below, this can happen when knowledge is *untight*, that is, the exact very certain and not easily verifiable by the rhetorical criteria of the time — as is for instance the case with homeopathic medicine.

Fourth, evolutionary models are rich in that they allow change to occur on different levels. In principle, of course, there is no reason to presume that evolutionary models should be confined to finitely-lived living beings endowed with a genotype derived from one or two parents, subject to differential reproduction. In other words, thinking in evolutionary terms boils down to what Mayr (1982, pp. 46–47) sees as the main power of evolutionary models, which is what he called "population thinking." As already noted, it stresses the importance of individual variation *within* populations and their ability to bring about changes in the many starting from the few. If we are interested in economic change at the macro level, such "population thinking" is critical.

There is a long debate whether this occurs in biological systems and what the appropriate "unit of selection" is. Some leading evolutionary biologists, such as George Williams and Richard Dawkins, feel that all selection happens at the level of the gene and nowhere else, but others strongly argue for selection at the level of the cell, the organism or the species and even populations. Whatever the outcome of this literature, it seems beyond question that in cultural evolution selection can happen at many levels. To see this, consider a novel cultural trait offered to an individual in a particular society. If the individual chooses the variant and not another, this is one level of selection at which choice-based cultural evolution occurs. Now assume, however, that this variant increases the fitness of this individual and thus extends his life expectancy and/or the number of surviving children who resemble him. This increases the chances that the trait will be passed on, either vertically through the socialization of offspring or horizontally through "infecting" his immediate neighbors. Furthermore, suppose that this society has now adopted the trait, and that it increases the fitness of this group (e.g., through more cooperation or adopting a superior technique); this may mean a higher population growth rate in a society that has adopted this trait, and thus is likely to increase its relative frequency in the global population. Evolution here is not a single process, but a complex and intertwined system of conscious choices and "natural selection" at different levels (Jablonka and Lamb, 2005).

Fifth, like all evolutionary systems, culture is resistant to change. In the technical language of evolutionary dynamics, prevalent cultural variants are evolutionary stable strategies with respect to most conceivable innovations ("mutants"). There are built-in mechanisms that maintain a certain stability and provide an advantage to incumbent cultural variants against innovations, but the effectiveness of these mechanisms is itself a function of the content of the system. Ernst Mayr (1989, p. 35) suggests that genes "perform as teams" and that "epistatic interactions form a powerful constraint on the response of the genotype to selection." Cultural elements, too, form a coherent system, which may resist change because of the interdependence of its components. Moreover, in cultural systems (with no obvious parallel in biology) culture is tied up with investments that people have made in the current beliefs and practices, and that would decline in value if the current beliefs were to be modified or overthrown. Physicists resisted quantum mechanics, physicians the germ theory, and chemists the atomic theory for precisely such reasons. No matter what kind of cultural system we are looking at, there will some resistance to change, and many seemingly "fit" innovations will fail in a hostile environment biased toward conservatism.[14] In other cases "cultural species" can coexist for very long periods indeed. The "new science" that emerged in the sixteenth and seventeenth centuries did not replace the Aristotelian orthodoxy in a few years or decades, but shared the

[14]Recently, economists (Benabou, Ticchi and Vindigni, 2013) have developed models to formalize the problem, pointing out that certain kinds of innovations reduced the value of existing ideas by being "belief-eroding" even if that was not their original intent. This creates an obvious conflict between those whose beliefs are being threatened and society at large, which stands to benefit from such ideas because they increase economic performance.

same environment, at times as substitutes but often in some kind of uneasy harmony or compromises that may seem implausible to us now.[15]

Sixth, any evolutionary framework implies that any easy generalizations or predictions about the speed and direction of cultural change are doomed. Most of the time culture changes at a tectonic pace, surviving dramatic institutional and political shocks. But there are instances when culture changes quickly as a result of weakened resistance, perhaps, or some powerful exogenous shock that challenges existing cultural beliefs deeply (Jones, 2006). Much like evolutionary science, the strength of the methodology is in helping us to make sense of the past rather than predict the future. Precisely because the unit of analysis continuously interacts strongly with its environment and because there are few time-invariant relations, it becomes unpredictable (Saviotti, 1996, p. 31). Moreover, as John Ziman (2000, p. 50) has pointed out, selectionist models stress that what matters in history is that often what matters is not statistical averages over large numbers of very similar states or agents, but rare events that get amplified and ultimately determine outcomes.[16] The challenge to historians then becomes to try to understand which rare events take on that function, and under what circumstances they get "selected."

Finally, an evolutionary approach gives us a more reasonable way of thinking about how and why historical trajectories were followed. It places the analysis firmly somewhere in the middle between a materialist approach that sees outcomes as inexorable and fore-ordained and a nihilist approach that sees randomness everywhere. The Great Divergence and the Industrial Revolution that caused it were neither fluke nor necessity, to paraphrase Jacques Monod's famous title (1971). Neither were the Scientific Revolution or the Enlightenment.[17] They arose because historical circumstances were conducive to the

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[15]An example is the rather quaint model of the solar system proposed by Tycho Brahe, the late sixteenth century Danish astronomer, who proposed a compromise between the Copernican model and the Ptolemaic one, in which the sun rotated around the earth but the other planets rotated around the sun.

[16]This has long been realized by evolutionary biologists, who have postulated that major evolutionary advances come from unusual and exceptional genotypes with opportunities to dominate their own small populations and radiate into marginal habitats. See Stebbins, 1969, p. 142.

[17]For a powerful statement in the same vein about the Scientific Revolution, see Cohen (2012, p. 204). He argues that the emergence of a "realist-mathematical" (i.e., modern) science was always a possibility, but its realization was not foreordained — we might still be living in a world in which Archimedes and Ptolemy still represented the summit of scientific achievement and the astrolabe and mechanical clock the supreme examples of toolmaking, with "death within a year of birth as the likeliest human fate by far."

sprouting of seeds that were already present in the soil. Evolutionary innovation occurs because a mutation takes place that happens in an environment that is favorable to it. But such a mutation is a minute subset of all the favorable mutations that might have happened, as well as of all the mutations that actually did happen but that did not turn out to be viable.

Evolutionary theory reminds the historian that not everything that happened had to happen, and that many things that could have happened did not. One of the most important implication of the small but fascinating literature in counterfactual history (e.g. Tetlock, Lebow and Parker, 2006) is to drive home the insight that history could have played itself out quite differently. It also reminds us that similar circumstances do not always lead to the same outcomes and that similar outcomes do not always have identical causes. The language of evolution suggests the distinction between homologies (similar outcomes due to similar origins) as opposed to analogies or homoplasies (similar outcomes with different origins). The work by economists on the interaction between culture and institutions reinforces this interpretation by recognizing that these models have multiple equilibria and that societies may start from very similar circumstances and yet end up in very different situations "depending on historical idiosyncrasies" (Alesina and Giuliano, 2014, p. 44). In both approaches, a guiding principle is that there was nothing inevitable about the actual historical outcomes we observe.

Evolution and Historical Issues

There are many issues in economic and technological history that can be re-explored using evolutionary ideas and terminology.

1. Does History make leaps? Does technological change occur in a gradual manner as Leibniz, Alfred Marshall, and the neo-Darwinian phylogenetic gradualist orthodoxy in evolutionary biology hold, or can it move in bounds and leaps as Eldredge and Gould and their followers in the "punctuated equilibrium" literature insist (Mokyr, 1990b)?[18] The debate parallels those in economic history

[18]In a classic but controversial work, the geneticist Richard Goldschmidt (1940) proposed a distinction between micro and macromutations. The former accounted for changes within a species, and were more or less continuous and cumulative. The latter accounted for great leaps in biological evolution that created new species. Goldschmidt believed that evolution moved at times in leaps and jerks through those macromutations. He argued, probably too rigidly, that new species arose only by way of macromutations and not by the continuous accumulation of micromutations. Following the emergence of a new species, it follows the standard evolutionary adaptive process of micromutation.

between scholars who believe in the Industrial Revolution and the great discontinuity it constituted and those who would deny this and see continuity everywhere.[19] The distinction between macroinventions (pathbreaking innovations that open new horizons) and microinventions (that fill fairly small gaps) proposed in Mokyr (1990a) is helpful here: every once in a while a new major technological leap forward opens a new technological chapter in history. The famous Dudley Castle atmospheric engine installed by Thomas Newcomen in 1712 may qualify as a "hopeful monster" in the Goldsmith tradition even if no biological examples for them are known to exist.

2. Are Darwinian models of natural selection sufficient to explain the course of history as the ultra-Darwinians such as Dennett and Dawkins claim, or do we need additional inputs from chaos theory, self-organization theory, or something yet unsuspected? Clearly these debates mirror those between the scholars who insist on multiple equilibria and hence path-dependence such as Brian Arthur (1994) and Paul David (1997), and their opponents such as Liebowitz and Margolis (1995) who feel that the rational market — if only left alone — will get it right every time and hence there is no need to worry about path dependence.

3. What exactly is the relation between the institutional environment, innovation, and technological selection, and can we distinguish meaningfully between adaptation and innovation? What kind of environment facilitates innovation? What is the nature of historical resistance to innovation and how is it overcome if it is? An example of the intersection of intellectual history and evolutionary models is the analysis of the "battle between the ancients and the moderns" that raged in the seventeenth century, in which European intellectuals overcame one of the most powerful forces of conservatism, namely the infatuation of learned people with the writings of earlier generation and the blind veneration of ancient learning, be it Aristotle, the Talmud, or Confucius (e.g., LeCoq, 2001).

4. Are traits invariably explicable in terms of their functions, as the fundamentalist adaptationists claim? Is there room in the history and analysis of technology for the notion of exaptation, for instance, which refers to cases in which an entity was selected for one trait but eventually ended up

[19]For an extreme example of this position, see Clark (1985), pp. 64-93.

carrying out a related but different function.[20] Concepts like "niches," "recombination," and "extinction" come naturally to the historian of technology, although they may not mean the same thing they do in biology.

5. Finally, we may ask in what sense can we think of "progress?" Biologists have long argued the point (with the late Stephen Jay Gould taking the strongest position against the notion of progress).[21] There seems to be no obvious way in which progress can be defined in the evolution of living beings. Is the same true in the history of knowledge? There are interesting questions around the "Panglossian" point that "whatever was, was good." Is it possible to rank outcomes using some kind of criterion, and assess to what extent historical outcomes were "desirable"? Economists find it natural to write of "technological progress" but normally discuss "institutional change" — an indication perhaps that knowledge is normally *cumulative* and therefore progressive, whereas in the change of institutions we can expect regress as often as progress (by some well-defined criterion).

Knowledge and Technique

In what follows, I shall briefly return to a framework described in Mokyr (2002) to highlight the advantages of an evolutionary approach in the economic history of technology. An evolutionary approach can help us clarify our thinking about useful knowledge, although analogies with biology and genetics can be misleading in many instances. Yet some parallels can be enlightening. Much like DNA, useful knowledge does not exist by itself; it has to be "carried" by people or in storage devices. Unlike DNA, however, carriers can acquire and shed knowledge so that the selection process is quite different. This difference raises the question of how it is transmitted over time, and whether it can actually shrink as well as expand. All carriers have finite lives and thus need to reproduce themselves in some fashion. The existence of nonliving carriers such as books and models, does expedite this transmission, but some crucial components cannot be codified

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[20]The term was first suggested by Gould and Vrba (1982). Historians of technology have of course long pointed to the phonograph and the digital computer as examples of such instances in economic history. Dyson (1997, pp. 81-82) draws the parallel explicitly: "feathers must have had some other purpose before they were used to fly...the same thing happened to ENIAC: a mechanism developed for ballistics was expropriated for something else."

[21]For an informed contrary point of view, see Vermeij, 1995, pp. 143-45; 2004, pp. 246-91.

or stored in devices that require codification. This "tacit" knowledge therefore dies with its live carrier unless it is passed on to the next generation. In this regard, evolutionary thinking points to the importance of apprenticeship in history, as the main mechanism by which knowledge was transmitted intergenerationally (Doepke, Delacroix, and Mokyr, 2016). The apprenticeship system is a classic case of Darwinian descent with variation: a craftsman absorbs from his master a set of skills, but adds his own variation which he subsequently passes on to his own apprentices. It might be added that knowledge received and knowledge transmitted are never quite identical, which is another source of innovation (Sperber, 1996, pp. 101–6).

It is useful to define the concept of the set of *useful knowledge*, an eighteenth-century term that roughly corresponds to our knowledge of science and technology. As already noted, we can segment this set into knowledge "what" or propositional knowledge (that is to say, beliefs) about natural phenomena and regularities and prescriptive knowledge "how," which we may call techniques. In what follows, I refer to propositional knowledge as Ω-knowledge and to prescriptive knowledge as λ -knowledge. If Ω is *episteme*, λ is *techne*.

The distinction between Ω and λ parallels the distinction made famous by Gilbert Ryle (1949; see also Loasby, 1996), who distinguished between knowledge "how" and knowledge "what." Ryle rejected the notion that one can meaningfully distinguish *within a single individual* between knowledge of a set of parameters about a problem and an environment from a set of instructions derived from this knowledge that directs an individual to take a certain action.

Is the distinction between propositional Ω-knowledge and prescriptive λ-knowledge meaningful? Both reflect some form of useful knowledge and thus are subject to the same kinds of difficulties that the economics of knowledge and technology encounters. An addition to Ω is a *discovery*, the unearthing of a fact or natural law that existed all along but that was unknown to anyone in society. An addition to λ is an *invention*, the creation of a set of instructions that, if executed, makes it possible to do something hitherto impossible. Michael Polanyi points out that the difference boils down to observing that Ω can be "right or wrong" whereas "action can only be successful or unsuccessful"(1962, p. 175).[22] Purists will object that

[22]Polanyi fails to recognize the important historical implications of the two kinds of knowledge and maintains that "up to [1846] natural science had made no major contribution to technology. The Industrial Revolution had been achieved without scientific aid" (p. 182). This bald statement surely will be accepted by no economic historian. The implicit definition he uses for Ω implies a much larger entity than formal science and includes much informal and folk

"right" and "wrong" are judged only by socially constructed criteria, and that "successful" needs to be defined in a context, depending on the objective function that is being maximized.

Rather than develop this framework in detail and show its historical applicability, which was the subject of Mokyr (2002), I want to stress here a few properties of the concept of knowledge that matter most to its role in technological development and economic growth. Perhaps the central one is the idea of an *epistemic base.* The epistemic base of any technique in use is basically the understanding of the natural processes that make it work. Yet what may not be true for an individual is true for society as a whole: for a technique to exist, it has to have an epistemic base in Ω. Some techniques can be made to work without any understanding of how and why they work: ancient humanity used fire for innumerable generation before the principles of combustion were understood; farmer hauled manure to their field before anybody understood soil chemistry.[23] Techniques were known to work; that was all that was needed.

Except that it was not. For one thing, *some* techniques cannot really be made to work unless something about the physics or biology underlying them is understood. This was even true about the first steam engine prototypes, built by Denis Papin in the 1690s: without the realization that a vacuum was possible and that the earth is surrounded by an atmosphere, the atmospheric engine would not emerged. The fuller epistemic base would have included thermodynamics, which was developed *as a result of* the steam engine. In that regard, the old adage that the steam engine did more for science than science did for the steam engine holds true — but with the proviso that absent a minimum epistemic base extant in 1700, there would have been no engine. With the Industrial Revolution, many new techniques emerged that grew symbiotically with their epistemic base, including electricity, organic chemistry and the industries based on it, and of course communications based on electromagnetic waves and pharmaceutical industries based on the germ theory of disease.

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knowledge. In addition to "pure science," he includes an intermediate set of inquiries that are "systematic technology" and "technically justified science." Moreover, his set of propositional knowledge must include even less formal elements when he points out that "technology always involves the application of some empirical knowledge... our contriving always makes use of some anterior observing"(Polanyi, 1962, p. 174). If so, the role of propositional knowledge of some kind in the development of technology must have been important long before modern science came into its own.

[23]The epistemic base in the limit can be infinitesimally small. If no knowledge whatsoever exists of why a technique works, then the epistemic base is trivially equal to the propositional statement that "the technique works."

For many of those industries, propositional knowledge and prescriptive knowledge *co-evolved*. Some minimum knowledge base is required to get the industry set-up, but after that the flows of knowledge go in both direction. The epistemic base of technology widened both because pure science made relevant discoveries and because of the feedback from the industry itself. No industry illustrates this better than steel: an ancient technique with a minimal epistemic base, growing insights as the role of trace amounts of carbon led to the development of cheap steel in the mid nineteenth century through the famous inventions of Bessemer and Siemens-Martin. Yet much experience and many serendipitous improvements made the product better and cheaper. After all, a major source of scientific insights come from the regularities and experiences learned in the production process itself.

In short, the relationship between Ω and λ is that each element in λ—that is, each technique—rests on a known set of natural phenomena and regularities that support it. It is not necessary for many people to have "access" to the epistemic base, but the people writing the instructions for the "new recipe" that constitutes an invention must be among them. They do not necessarily have to possess the propositional knowledge themselves, but they must be able to access it, for instance by consulting state-of-the-art scientists. The historical significance of the idea of an epistemic base is not just that there is a minimum base without which some techniques could not be conceived. It is above all that the wider and deeper the epistemic base on which a technique rests, the more likely it is that a technique can be extended and find new applications, product and service quality improved, the production process streamlined, economized, and adapted to changing external circumstances, and the techniques combined with others to form new ones.[24] When an existing technique needs to be extended or adapted to different circumstances, the content and extent of the epistemic base become important, and the practitioners return to the "theorists." Trial and error and try-every-bottle-on-the-shelf might work, of course, but it is more uncertain, slower, and far more expensive. If some-one, somewhere, knows the regularities and natural laws that make the technique work, that knowledge can be invoked or that expert can be consulted. In a word, the rate and scope of technological progress depends

[24]This argument was well formulated by William Rankine, the great Scottish engineer, in 1859, when he noted that normal progress consists of "amendments in detail of previously existing examples." However, when the laws on which machines operate have been reduced to a science, practical rules are deduced "showing not only how to bring the machine to the condition of greatest efficiency...but also how to adapt it to any combination of circumstances" (Rankine, [1859] 1873, p. xx).

on inventors and technicians to understand what they are doing and why it works. The growth of science in the century and a half since the appearance of Antoine Lavoisier's seminal *Traité élémentaire de Chimie* in 1789. Of course, this insight itself could be gained even without any recourse to Darwin. But the notion of a dual structure that parallels that of a co-evolving genotype and phenotype is helpful here (Blackmore, 1999, pp. 93-107; Jablonka and Lamb, 2005).

To pursue the commonality just a bit further: not every gene ends up coding for a protein, but for any phenotype to emerge, *some* basis for it has to exist in the genome. However, much like parts of the DNA that do not code for any protein, some exogenous change in the environment may bring about the activation of hitherto "dormant" useful knowledge. Similarly, techniques exist that are known but currently not used, but which could be brought back with the right kind of stimulus. Economists familiar with isoquants will find that conclusion familiar. More complex, environmental changes may trigger interactions between existing genes leading to epistatic effects.

As noted, it is not necessary that the person actually carrying out the technique possess the supporting knowledge. One can bake a cake from a recipe without understanding the microbial actions of yeasts. I typed these lines on a computer even though I have only rudimentary knowledge of the physical and mathematical rules and principles that make my computer work. It is likely that the workers who put together my laptop did not possess this knowledge either. To distinguish the knowledge needed to invent and design a new technique from that needed to execute it, I shall refer to the latter as *competence*. Competence is defined as the ability of agents to carry out the instructions in λ. The codified knowledge in the instructions still needs to be decoded, and in part competence consists of the ability to do the decoding, or if a codebook is supplied, to decode the codebook. Tacit knowledge is an essential part of competence. It is needed for obtaining inexpensive and reliable access to the codified instructions. Moreover, no set of instructions in λ can ever be complete. It would be too expensive to write a complete set of instructions for every technique. Judgment, dexterity, experience, and other forms of tacit knowledge inevitably come into play when a technique is executed. Another element of competence is the solution of unanticipated problems that are beyond the capability of the agent: knowing whom (or what) to consult and which questions to ask is indispensable for all but the most rudimentary production processes.[25]

The epistemic base of a technique does not have to be invoked consciously each time the technique is carried out. Much of it is front-loaded in the instructions specified and the artifacts and equipment deployed, and the instructions themselves rarely need to explain why the recommendations work. Nor does every user have to possess the entire competence involved in operating the technique. The nature of social knowledge is that such knowledge is not necessary for everyone concerned. Hence the assumption, often made by economists, that the stock of technical knowledge is accessible to all economies seems reasonable. It seems plausible that competence—the capability to deploy a technique—is usually easier to acquire than the epistemic base. Thus even in countries where only a few people understand the finer points of electronics and microbiology, smartphones and antibiotics can be produced and used. Yet how effectively techniques are deployed may differ a great deal from society to society even if the artifacts are identical, because competence depends on tacit knowledge and cultural traits that may differ systematically.

The set of propositional knowledge Ω thus maps into the set of techniques (prescriptive knowledge) λ through the epistemic base, and thus imposes a constraint on it much as the genotype maps into the phenotype and constrains it without uniquely determining it. The rather obvious notion that economies are limited in what they can do by their useful knowledge bears some emphasizing simply because so many scholars believe that if incentives and demand are right, somehow technology will follow automatically. Even a scholar as sophisticated as Eric Jones believes that "technology seems to offer 'free lunches' but its spectacular gains are really secondary; they are attainable by any society that invests in institutions to encourage invention and enterprise" (2002, ch. 3, p. 20).

Yet throughout history things that were knowable but not known were the chief reason why societies were limited in their ability to provide material comforts. Certain societies, including our own, did not have access to some feasible techniques that would have benefited them a great deal because they lacked a base in Ω. Medieval Europe could not design a technique describing the ocean route to Australia or produce antibiotics against the Black Death. The age of Enlightenment could not produce electrical light or

[25] Teece et al. (1994) correctly point out that the firm's "competence" includes some skills complementary to purely technical capacities such as knowledge of markets, sources of supply, finance, and labor management.

antibiotics. Our own societies have been unable to tame nuclear fusion and make effective antiviral agents because we do not know enough about high-energy physics and virology. Nonetheless, we cannot be sure that such knowledge will never exist; all that matters is that we do not have it. In that sense, again, a certain similarity with evolutionary biology emerges. It is likely that certain species of high fitness *could have* evolved if the right mutations had emerged, but that these mutations simply did not occur.

In the history of useful knowledge, we can be a bit more specific that than. While in nature mutations occur because of random errors in the transmission of genetic material, scientific advances, though they have a stochastic element, can be understood. The main reasons scientific breakthroughs occurred are related to the tools that scientists have at their disposal and the agenda that institutions and culture dictate. The Scientific Revolution of the seventeenth century was in large part driven by a number of new instruments that came online: the telescope, the microscope, the barometer, the thermometer, the vacuum pump. The second Industrial Revolution of the late nineteenth century, similarly, was driven by a set of new tools and instruments that drove research. In that fashion, technology pulled itself up by its bootstraps: new research tools created new science, and the new science then created new technology across a wide spectrum.[26]

How and when does Ω provide the epistemic bases for technology? For people to willfully create a new technique, they have to believe that some underlying propositional knowledge is likely to be correct. The mapping of the route around the globe was based on the belief that the earth was spherical, much as aseptic methods are based on the belief that bacteria cause infectious diseases. One of the more important characteristics of propositional knowledge and its role in supporting technology is not only the width of the epistemic bases of technology but also the *tightness* of knowledge. Tightness has two dimensions: confidence and consensus. The tighter a piece of knowledge is, the more certain the people who accept it are of their beliefs, 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 number, but many Americans still do not believe in the Darwinian theory of evolution and still believe in the possibility of predicting human affairs from looking at the stars.

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[26]A fascinating example is the development of x-ray crystallography around 1915 by a father and so team named Bragg; the technique was applied to a plethora of scientific projects, none more path breaking than the work of Rosalind Franklin, the co-discoverer of DNA.

Tightness depends on the effectiveness of verification, that is, the extent to which rhetorical conventions accepted in a society persuade people that something is "true," "demonstrated," or at least "tested." It defines the confidence that people have in their knowledge and—what counts most for the purposes of technological change—thus their willingness to act upon it. The tightness of the knowledge in Ω also determines the extent to which people are willing to employ the techniques that are based on it. This is particularly relevant when the outcome of a technique itself cannot be assessed immediately.[27] Techniques may be "selected" because they are implied by a set of knowledge that is gaining acceptance rather than by any direct measurement of their effectiveness.[28] It is important to stress that tightness is in no way an ordering of knowledge: it is purely a social construction. The Ptolemaic universe and Galenian medicine were forms of tight knowledge in medieval Europe, in the sense that practically everyone who mattered believed in them and did so with a high degree of confidence on the basis of their trust in ancient authorities. As the rhetorical conventions changed after 1500, doubts crept in and the knowledge became looser.

Finally, where social science departs from evolutionary biology is in the social dimensions of knowledge. In the end, what each individual knows is less important than what society *as a whole* knows and can do. Even if very few individuals in a society know quantum mechanics, the practical fruits of the insights of this knowledge to technology may still be available just as if everyone had been taught advanced physics. For the economic historian, what counts is *collective* knowledge. But collective knowledge as a concept raises serious aggregation issues: how do we go from individual knowledge to collective knowledge beyond the mechanical definitions employed above? The knowledge available to society as a whole is the *union* of all sets of knowledge residing in individuals, reflecting the inevitable division of knowledge in advanced societies. Making it available to those who need it depends on access. Progress in exploiting the existing

[27]Many techniques can be selected by individuals on the basis of readily measured characteristics: laser printers are preferred to dot matrix printers for the same reasons air-conditioning is preferred to room-fans. But in many other cases the judgment is difficult: Does broccoli consumption reduce the risk of cancer? Do nuclear power plants harm the environment more than fossil fuel-burning generators? In those cases, people might choose the technique that is based on the tighter Ω. More people choose antibiotics over homeopathic medicine or Christian Science when they suffer from a disease whose etiology is well understood.

[28]If techniques implied by rather untight knowledge can be shown to be effective. Knowledge in Ω will become tighter and more difficult to resist if it maps into techniques that actually can be shown to work. To put it crudely, the way we are persuaded that science is true is that its recommendations work visibly (Cohen and Stewart, 1994, p. 54).

stock of knowledge will hence depend first and foremost on the efficiency of distribution and the *cost of access* to knowledge possessed by others. What makes knowledge a cultural entity, then, is that it is distributed to, shared with, and acquired from others; if that acquisition is too costly, important Ω-knowledge will not be accessible to those who do not have it but are seeking to apply it. As the amount of knowledge expands, the fraction of it contained in the mind of an individual will decline and the importance of access technology increases.

Between the two extreme cases of a world of "episodic knowledge" as it is said to exist among animals and a world in which all knowledge is free and accessible to all at no cost, there is a reality in which some knowledge is shared, but access to it requires the person acquiring it to expend real resources. Access costs depend on the technology of access, the trustworthiness of the sources, and the cultural norms of "sharing knowledge."[29] It also depends of course on the total size of Ω; the larger Ω, the more specialization and division of knowledge is required. Experts and special sources dispensing useful information will emerge, providing access. Information technology (IT) is exactly about that. The inventions of writing, paper, and printing not only greatly reduced access costs but also materially affected human cognition, including the way people thought about their environment.[30] But external memory came at a cost in that it codified and in some cases crystallized useful knowledge and gave it an aura of unassailability and sanctity that sometimes hampered the continuous revision and perfection. All the same, the insight that the invention of external storage of information is much like networking a computer that previously was a stand-alone has some merit.[31]

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[29]The emergence of "open science" in early modern Europe, in which new useful knowledge was placed in the public realm through correspondence or publication and made accessible to others who had the tools to understand the texts, should be regarded as a major access-cost-reducing cultural development (Dasgupta and David, 1993; David, 2008).

[30]The invention of such "external storage systems" has been credited by Merlin Donald (1991, pp. 308–12, 356) as the taproot of modern technological culture.

[31]Elizabeth Eisenstein (1979) has argued that the advent of printing created the background on which the progress of science and technology rests. In her view, printing created a "bridge over the gap between town and gown" as early as the sixteenth century, and while she concedes that "the effect of early printed technical literature on science and technology is open to question" she still contends that print made it possible to publicize "socially useful techniques" (pp. 558, 559).

Innovation and Inertia

Evolution is inherently conservative. In all evolutionary systems, technological systems included, there is considerable inertia and constraints on change (Nelson, 1995, p. 54). In evolutionary models of technology, because of the dynamic structure of evolution in which knowledge depends on past knowledge, technical innovations (that is, additions to λ) are likely to be extensions and modifications of existing techniques. Most inventors and technological historians have thought of innovation as largely a set of new combinations of existing knowledge.[32] Weitzman (1995) sets up a model in which invention is essentially nothing but a recombination of existing technology. Yet this seems confusing at second thought: it is not the techniques *themselves* (much less the artefacts in which they are embedded) that are combined as much as the knowledge underlying them. This may appear a distinction without a difference. Only if the technique is a singleton are these processes undistinguishable. It should be noted that complementarity rarely involves "similarity" and the elements to be recombined often come from what Adam Smith in the famous first chapter of *the Wealth of Nations* already called "the most distant and dissimilar objects" -- in my terminology totally different subsets of Ω, for instance software and hardware, or the electrical components of an automobile with the transmission.

For whatever reason, some evolutionary systems change rapidly and frequently while others remain in stasis for very long periods. In biology we observe periods of very rapid change known sometimes as "adaptive radiation." Even when such rapid change occurs, for whatever reason, it is important to realize that the genetic structure of living beings is subject to inertive mechanisms, which all evolutionary systems need to have unless they are to slide into chaotic mode. These inertive mechanisms are set up to resist change; without them the system would clearly become unstable and likely to end up in what Stuart Kauffman (1995) has called the hypercritical region in which change becomes uncontrollable and unrestrained.

In biology the resistance shows up first in the absence (or extreme rarity) of anything that resembles a Lamarckian mechanism. A genotype is set upon meiosis. If Lamarckian change could occur, the rate of

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[32] Usher (1929, p. 11) felt that "invention finds its distinctive feature in the constructive assimilation of pre-existing elements into new syntheses" but in the revised (1954) edition of his book admitted that strategic inventions "comprise both old and new elements" (p. 68).

change of an evolutionary system would be vastly more rapid, and stability would be unthinkable.[33] Within the Weissmanian constraints change is very rare, and resistance to change is built in at any stage.[34] While such genetic cohesion has of course not precluded the well-known adaptive radiations that created different species, these explosions of variety are little more than ad hoc variations on a single *bauplan* or structural type. This cohesion, while not wholly understood, is essential to the development of the world of living species: the key to success is to strike a compromise between excessive conservatism and excessive malleability. Evolutionary systems, whether biological or other, that are too conservative will end up in complete stasis; too much receptivity to change will result in chaos (Kauffman, 1995, p. 73).

Such resistance also exists in knowledge systems. Technological resistance has a number of different sources and mechanisms but it is a property of *all* evolutionary systems, including cultural ones. Consider language: grammatical errors, and spelling mistakes are weeded out mercilessly by the red pencils of English teachers and copy-editors. Yet neologisms, new usages, novel forms of spelling and even grammatical rules do eventually make it through or languages would remain immutable over long periods. It is just that only the tiniest fraction of them ever have a chance, and of those another very tiny fraction gets selected. In technology it is a direct consequence of superfecundity in the set λ: a lot of new ways to carry out a particular production are "proposed" or "occur to individuals," but unless the vast majority of such suggestions are rejected, the cost of continuous experimentation and change would become unbearably large.

Even for unequivocally superior techniques, however, resistance is likely because given the finiteness of the number of techniques in use, they are likely to replace and displace existing techniques. In knowledge systems, existing techniques are embodied in agents using them, and these agents operate as intentional and rational agents. Incumbent agents will sustain losses if the new techniques are adopted through the devaluation of their human and physical capital and they are likely to resist. Even at the level of Ω it is conceivable to think of cases in which resistance to innovation occurred because of "vested interests" in

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[33] I am indebted to my late colleague David Hull for this insight.

[34] As Mayr (1991, pp. 160-161) has explained, "Just exactly what controls this cohesion is still largely unknown, but its existence is abundantly documented...during the pre-Cambrian period, when the cohesion of eukaryote genotype was still very loose, seventy or more morphological types (phyla) formed. Throughout evolution there has been a tendency for a progressive "congealing" of the genotype so that deviation from a long-established morphological type has become more and more difficult."

certain. For instance, a complex religious culture in which some elements are out of tune with perceived reality may either adapt to reflect new beliefs or cling to increasingly antiquated beliefs (Benabou, Ticchi and Vindigni, 2014). The power structure within the organizations that depend on these beliefs (as is the case with the Catholic church today) may either dig in and fiercely resist change, or it can adapt. Yet when there are few direct interests at stake, and when rhetorical devices such as mathematical proof, statistical significance, and experimental evidence are well-developed and widely accepted, resistance to new knowledge about nature that meets those rhetorical tests tends to be short-lived and moribund. While Copernicus, Lavoisier, and Darwin all ran into well-determined and well-organized resistance, the outcome was never in doubt. This is much less true for new techniques. In part, techniques could be untight, in the sense that it is difficult to establish their superiority. But there is far more involved.

As a first approximation, the struggle against nature is not a social activity. One can imagine a solitary individual with a certain knowledge available to her, who maps from it to solve the material problems of survival. While almost immediately one can think of social dimensions of this game, the control and manipulation of nature in what we call "production" is in the first instance not a social activity but an environmental one. Once we admit, however, that in any kind of organized group technological activity becomes something that involves others as well, there are new opportunities but also new constraints on individual action. In part, technology becomes something of a social consensus, "the way we do things" and the individual must face up to the fact that when she wants to deviate from this norm, some measure of consent and cooperation from others has to be secured.

Every act of major technological innovation, then, is an act of *rebellion* not just against conventional wisdom but against existing practices and vested interests, and thus will normally lead to some kind of resistance.[35] In what follows below I will discuss the latter in an attempt to assess the historical sources of resistance to technological innovation. In the history of technology we can distinguish a number of different sources of resistance. None of these have *exact* counterparts in evolutionary biology nor should we expect there to be any; what matters is that there is resistance to change.

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[35]The literature on the subject has been growing rapidly in recent years. For a recent useful collection, see Bauer, 1995; A one-sided and popularized account is Sale, 1995. See also Mokyr, 1994, 1998b, 2002, pp. 218-83.

1. *Economically motivated resistance*: groups or individuals with a stake in the incumbent technology may resist change because a switch to a newcomer may benefit other groups at their expense. Workers in danger of losing their jobs, facing changes in their work environment, or fearing that their human capital will depreciate are one example of this, but many others can be mentioned as well. In the Benabou, Ticchi and Vindigni (2014) framework, scientific progress leads to technological progress, but at a cost: it erodes religious beliefs, and that reduces the utility and rents of those who were vested in religion; in their model, there is a State that has the option to either permit such innovations to spread, or can try to censor them and prevent them from spreading
2. *Ideologically motivated resistance*: these include various sources of political resistance that are not fueled by direct economic motivation: technophobia, neophobia, a sense that meddling too much with the creation and nature is in some way sinful, or a high degree of risk aversion with particular high cost associated with low-probability catastrophic events such as nuclear accidents. Much of the resistance to nuclear reactors, GMO's, stem cell research, and cloning can be read this way, as do attitudes such as "we should not play God," or "if it ain't broke, don't fix it." The most obvious way such resistance takes, then, is as an ideology of *conformism* in which deviancy -- whether technological, political, religious or ethnic -- is actively discouraged.
3. *Epistemological resistance*: The flip side of the relationship discussed above between knowledge of nature and its manipulation implies that techniques might be resisted when they are seemingly contradicted by an element in Ω that currently enjoys "accepted" status, especially when it does not have a strong base in Ω itself. Thus when quinine was first introduced into Europe, it was resisted for a number of reasons, at least one of them being that it did not mesh with accepted Galenian practice (Duran-Reynals, 1946, pp. 45-53). Smallpox vaccination was resisted strongly and anti-vaccination movements sprung up (Knapp, 1989, pp. 265-66). The public had after all good reason to be suspicious of the recommendations of doctors, and it took decades and a determined propaganda campaign to convince a reluctant populace of the blessings of vaccination. Similarly, Dr. Barry Marshall's suggestion in the 1980s that peptic ulcers were caused by bacteria was resisted because "accepted" knowledge suggested that bacteria could not survive in the acid stomach lining. Such resistance can be overcome, and often is when the techniques are sufficiently tight so that

results can be readily demonstrated to conform to the rhetorical conventions of persuasion, as was the case with smallpox inoculation. In many cases in the history of technology the "proof of the pudding was in the eating" and simple observation and experimentation were enough to persuade skeptics that even if an invention flew in the face of accepted knowledge it worked better and too bad for accepted knowledge. But when techniques are techniques are untight such as acupuncture, astrology, mind-reading, and other techniques not firmly based on an accepted part of Ω, they are still regarded with great scepticism by most selectors even if they are widely used by others. An especially telling example is the polygraph machine which relies on a questionable foundation in natural knowledge and whose actual effectiveness, much like homeopathic medicine is controversial yet remains in wide use (Alder, 2007).

4. *Strategic complementarities*. A considerable number of technological breakthroughs in history failed to gain widespread implementation because of the absence of strategic technological complementarities. Without the right tools, the right materials, and the necessary skilled workmanship, good ideas simply could not make it from the drawing table to the prototype and certainly not from the prototype to mass production. The difference between James Watt and Leonardo Da Vinci, both enormously original and creative technological geniuses, was that Watt had first rate instrument makers and cylinder drillers at his disposal. Hot-air ballooning could not become an effective means of transportation until light-weight sources of motive power could be made that solved the problem of direction; electrical power could not become a widespread means of energy transmission till the problem of cheap generation through self-excitation was resolved. Often an invention depends on the solution of sub-problems. If these remain unsolved, an invention will be stillborn (e.g., Arthur, 2009, pp. 116-19).

5. A very similar phenomenon occurs in the presence of *systemic resistance*. As long as technology consists of individual components that can be optimized independently, changes in individual techniques depends on those of others only through the price mechanism. In other words, a change in a particular technique will drive up demand for complements and reduce that for substitutes. As long as there are no strong network externalities, it may not matter what happens to other techniques.

But such externalities have always existed, even if their extent may have been limited.[36] If the costs and benefits of the adoption of a technique depend on the technique's ability to match with existing components of a given platform, the process of innovation has to take this into consideration. Technological change in a "system" becomes a coordination game which may have multiple stable solutions. Once settled on a solution, it may require a substantial cost advantage for the system to move to a different one (Loch and Huberman, 1999; Witt, 1997b). In our own age, network externalities (broadly defined) place serious limits on the degree and direction technology can change at any given time. The concept of a "lock-in" into an existing outcome is the most extreme case. Normally all that occurs that a finite but considerable cost has to be paid to make the switch. A new technology will need either to fit in with the existing system or be able to create a "gateway" technology that will somehow create a bridge between it and existing components.[37] Software has to be "windows-capable," electrical tools require 115 V, car engines are constrained to gasoline and diesel fuels. As noted, such standardization problems can be overcome, but they impose a high transition cost and thus a constraint on new techniques, and constitute a source of resistance. At times, such situations lead to ex post inefficient outcomes believed to require government intervention.

6. *Frequency dependence*. In many cases, the rate of technological change and the rate of adoption depends on the number of users. Frequency dependence is a prime example of systems with positive feedback (Arthur, 1994) and exhibit certain non-ergodic properties more common in evolutionary systems than in standard economics. Economies of scale (within a firm), external economies (among different firms), and learning by doing effects fall into that category, as do all models with network economies in communication, such as fax machines, instant messaging, and social media (thus blending with systemic properties in category 5). Frequency dependence is also

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[36]It is sometimes thought that "technological systems" in T.P. Hughes's celebrated definition did not come into being till the Industrial Revolution (see for instance Edward Tenner's (1997) otherwise brilliant book, p. 13). Yet open field agriculture was clearly a complex system in which individual components such as crop choice could not be optimized independently of the whole. The same is true for the sailing ships, a complex entity in which rigging, masting, hull and steering all depended on each other and jointly determined the parameters of the vessel.

[37]For an interesting historical example see Puffert (2009).

more likely to play a role in technological change when the technique is untight so that the benefits of an innovation are hard to observe. Selectors will look at what their neighbors do and emulate them, trying to save information costs.

In short, resistance to the new exists at various levels, and if innovations are to occur at all, they have to overcome these barriers. Much like mutations, then, innovation should thus be regarded as a three-stage process, or a "pyramid of causality" (as Arthur, 2009, p. 124 has called it). First, will the new techniques occur at all? Second, if the innovation does take place, does it overcome the initial resistance? Third, if it survives, it will be tested on the merits of its own traits and will it become fixed in the population or at least carve out a sustainable niche? The question that needs to be asked is not, why is there no more innovation, but why does innovation occur at all – how does it succeed in overcoming the first and second stage barriers? There is no single answer to that question, of course. There have been inventions in history which have been so truly overwhelming in their superiority that no effective resistance could be put up. The mechanical clock and moveable type, a quarter of a millennium apart, simply swept Europe off its feet. Both of them were "macroinventions" by the standards described above. Among the nineteenth century inventions, the telegraph, aniline purple dyes, and x-ray photography were of that nature. These advances were all quite tight: the improvement in the desired traits were easily verified and all but impossible to dispute. They did not need to fit into an existing system. But many other breakthroughs encountered resistance of one form or another. In our own age, nuclear power, high-definition TV, and genetic engineering are noted examples (though the roots of resistance to each of those is quite different). The economic historian, stimulated perhaps by other cases in which evolutionary systems overcame resistance and produced sudden spurts of rapid evolutionary change, should continually ask what kind of environment and what type of community tend to be conducive to such sea changes?

Conclusions

The use of evolutionary models in economic history, despite many calls for it, has yet to materialize. While important work has been written using Darwinian ideas to explain economic history, they have relied on standard population dynamics rather than on the much more promising area of evolutionary epistemology

(Galor and Moav, 2002). The application of evolutionary thinking to the economic history of technology, pioneered by the now canonical work of Walter Vincenti (1990) and Edward Constant (1980). It has turned out that evolutionary paradigm, despite its many attractions described above, has yet to make a serious impact.

With the growing interest of economics in culture and cultural factors in economic growth (e.g., Alesina and Giuliano, 2016; Fernandez, 2011), evolutionary thinking may become increasingly interesting to economists because of its obvious applicability to cultural dynamics. For economic historians, this is particularly interesting because of the centrality of scientific and technological progress in modern economic growth and because science and technology are in the final analysis things we know and believe and thus cultural phenomena. If we accept that "useful knowledge" consists of cultural variants in which innovations struggled to be accepted in a Darwinian competitive "red in tooth and claw" environment, its full implications for the emergence of a modern economy are obvious. Specifically, it helps us understand how, in the critical centuries between Columbus and Newton, the selection environment in the European market for ideas changed in a way that made it more receptive to new ideas and in which the fitness of cultural variants was redefined to create a world in which "progress" itself became a successful cultural item (Mokyr, 2016).

None of this suggests that concepts from biology can and should be adapted in unaltered form into economic history, or any other field in economics. But the power of evolutionary thinking in understanding how cultural dynamics and the progress of science and technology to change our economies stands undiminished. Above all, it teaches us the hazards of hindsight bias and strong contingent nature of some of the central developments in economic history, in contrast with materialist modes of thinking. And yet, it also warns us that History is not random accidents. Contingency should not be overdone, and evolutionary theory, while making substantial allowances for contingency, does not imply sheer randomness. We can make sense of the past.[38]

[38]Joseph Needham, originally trained in biological science, warned that to attribute "the origin of modern science" entirely to accidental factors would be tantamount to admitting the bankruptcy "of history as a form of enlightenment" (1969, p. 216).

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