in Brezis, E.S. and P. Temin. 1999. *Elites, Minorities and Economic Growth*, North-Holland, Elsevier.

CHAPTER 14

INVENTION AND REBELLION: WHY DO INNOVATIONS OCCUR AT ALL? AN EVOLUTIONARY APPROACH*

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1. Introduction

How are we to think of the *fundamental* causes of technological change? I should like to propose -- although not demonstrate -- that standard neoclassical economic models perform poorly in explaining technological progress. In a recent paper, Prescott (1997) noted the failures of standard theory to explain the huge differences in incomes and productivity. Instead of criticizing standard analysis again, I suggest experimenting with an alternative. In this chapter I will sketch out the rough outlines of a model based not on standard neoclassical analysis but on evolutionary dynamics. The idea that knowledge can be analyzed using an evolutionary epistemology based on blind variation and selective retention was first presented by Campbell (1987) and has since been restated by a number of scholars in a wide variety of disciplines.[1]

In previous work, I have outlined the potential of the use of evolutionary biology in the economic history of technological change.[2] A reasonable criticism of such arguments has been that whereas models of blind-variation with selective retention are an instructive way to look at innovations, they add little direct insight that cannot be gained from standard models. I will argue that the role of small groups and minorities in creating innovations broadly defined is a counter-example to such criticisms and that evolutionary models provide a theoretically cogent framework that cannot be attained from standard neoclassical models. The unit, I am interested here, is not a living being as Darwin was, but an epistemological one, the *technique*. The technique is in its bare essentials nothing but a set of instructions, if-then statements (often nested) that describe how to manipulate nature for our benefit, that is to say, for production widely defined.

I will first lay out the groundwork for an evolutionary analysis of technological knowledge, and briefly examine how it changes (or does not) over time. I will then analyze why relatively small units might have an advantage here, and finally apply this model to retell the story of the economic importance of the city-state in technological history.

2. A Few Definitions

We first 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. Darwin himself recognized the applicability of random variation with selective retention to changes in language. North (1990) suggested a similar approach to the development of economic institutions, Dawkins (1976) to the realm of ideas (*memes*), Cavalli-Sforza and Feldman (1981), and Boyd and Richerson (1985) to culture, Elliott (1985) to the analysis of Law, and Dennett (1995) to practically everything. The biological reproduction of living things in this scheme of things turns out to be a rather special case of a broad set of this type of dynamic models. The main idea of a Darwinian model is a system of self-reproducing units (techniques) that changes over time. A Darwinian model must contain, in my opinion, three fundamental elements (Mokyr, 1999).

One is the notion of the relation between an *underlying structure* that constrains but does not entirely determine a *manifested entity*. In biology, the underlying structure is the genotype; the manifested identity is the phenotype. The relation between the two is well understood, although there is still an endless dispute of their respective contribution. In the history of technology, the underlying structure is the set of *useful knowledge* that exists in a society. The idea that such a set can be defined dates back to Kuznets (1965). It contains all "knowledge" and beliefs about the natural world that might potentially be manipulated. Such knowledge includes the cataloguing and identification of natural phenomena, including regularities and relationships between them. This set, which I will call Ω, contains but is not confined to consensus scientific knowledge. It also contains beliefs, traditions, superstitions, and other knowledge systems that may not get down to the principles of *why* something works but all the same codify it. It certainly contains discredited and erroneous theories or theories that will subsequently be refuted. A good example might be the humoral theory of disease or the Ptolemaic description of the Universe. As long as these beliefs are held by *somebody* they must be included in Ω which is the union of all such beliefs. It might also contain singletons such as "this procedure works though we are clueless as to why."

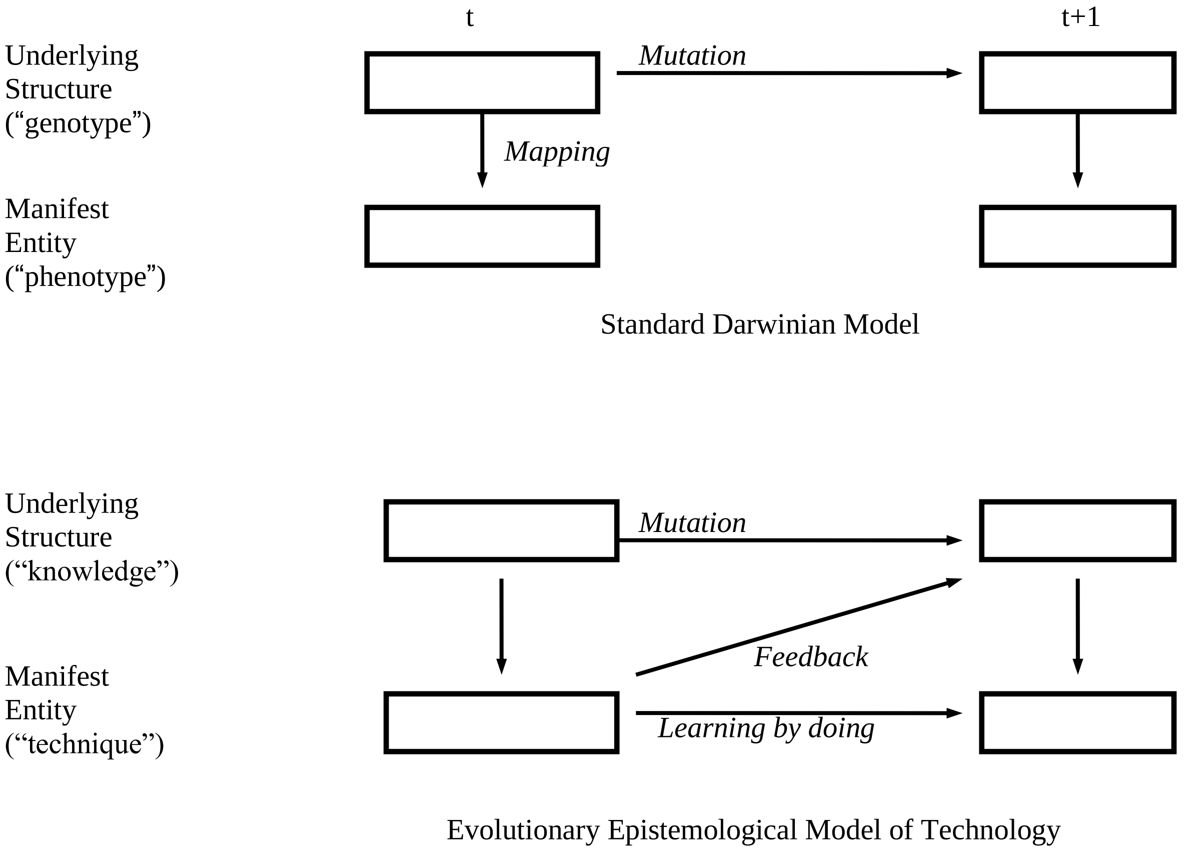
The critical point is that the elements in this set maps into a second set, the manifested entity, which I will call the feasible techniques set λ. This set defines what society can do, but not what it *will* do. Each technique is a set of instructions that yields an outcome, and the outcome is then evaluated by a set of selection criteria that determines whether this particular technique will be actually used or not. This selection is similar to the way in which selection criteria pick living specimens and decide which will be selected for survival and reproduction and thus continue to exist in the gene pool. The elements in λ differ from those in Ω in that they define our power over nature and not just our knowledge over it, similar to Ryle's famous distinction of "knowledge how" as opposed to "knowledge that." Thus the humoral theory mapped into techniques such as bloodletting and the Ptolemaic theory, implied certain rules about navigation and the determination of latitude. The analogy between the mapping of genotype to phenotype and the mapping of underlying knowledge to technical practice in use is inexact and to some extent forced: while genomes will vanish as soon as the species is extinct, knowledge can continue to exist even if the techniques it "codes for" are no longer chosen. All the same, the bare outlines are quite similar.

Second, any Darwinian model must be a dynamic system of change over time, a stochastic process of some definable characteristics. As Nelson (1995) asserts, these models are in a class that is more or less halfway between deterministic and purely random dynamic systems, what he calls "somewhat random variation." At each moment, the state of the world is given but simultaneously, there are stochastic innovations (that could be wholly random but do not have to be). These innovations create a fortuitous variation that defines the options for the system to move to. In this kind of model, techniques "reproduce" from period to period and thus "carry" the knowledge embodied in them over time. In this view, a technique uses human agents to reproduce itself to make another technique much like, in Samuel Butler's famous quip, "a chicken is the way an egg produces another egg." It seems plausible, for instance, to think of it as a Markov chain in which the state in time t is dependent entirely on the state in $t-1$; earlier history does not matter since it is entirely encapsulated in the state at t. "Extinction" could then be thought of as an absorbing barrier. How do techniques reproduce themselves? The most obvious mechanism is through repetition. If a truck driver follows the instructions how to get from Cincinnati to Kansas City, and then does so again, the technique has reproduced itself. If the agent changes, which in the long run has to be the case, learning and imitation take place. But as long as we insist that the technique itself is the unit of selection, the identity or characteristics of the agent is not the main subject of discussion. There are many ways to drive from Cincinnati to Kansas City and among those certain specific routes are selected and others are not. Because the number of uses of each specific technique changes over time (as a function of certain "traits"), evolutionary processes belong to a special group of Markov chains known as "branching processes." In these models each unit reproduces a number k of offspring, where k is a random variable. 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 accidental (David, 1992, 1997). A multiplicity of conceivable outcomes with the actual result often determined by historical contingency is thus part of the process. Yet it is not quite the same as the standard problems that occur in economics with multiple equilibria and the need to refine them. As Witt (1997) 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.

Again, the evolutionary dynamics differ in some important way between living beings and techniques. In living beings, persistent change occurs only through gene mutation and direction occurs through selection on the living beings that carry them. In technical knowledge systems, there are two stochastic processes at work. First, the useful knowledge reproduces itself over time with possible "mutations" (discoveries about natural phenomena). Second, the techniques also reproduce themselves and changes can occur, for instance, through experience and learning by doing. These two processes are clearly related, with feedback going in both directions. This feedback occurs through the impact of new techniques on knowledge, e.g., the invention of telescopes that affected astronomy, or the impact of early steam engines on the development of theoretical physics. Such feedback does *not* occur in living beings, where Lamarckian feedback mechanisms from phenotype to genotype are ruled out. This two-pronged stochastic process is depicted in figure 1.

Third, there is a property of superfecundity in the system, that is, there are more entities that can be accommodated, and there must therefore be some selection in the system. This selection process is what drives the entire system by determining the likelihood that a certain technique will be actually used. The nature of superfecundity in epistemological systems is a bit different than in Darwinian biology, where entities reproduce at a rate that is faster than can be accommodated by available resources. In the world of technology it 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. Unlike Darwinian models, selection is not a metaphor for an invisible-hand kind of

FIGURE 1



mechanism that operates in a decentralized and unconscious manner; there are actually conscious units, firms and households, that do the selecting.[3] Because in knowledge systems, storage of information does not have to occur exclusively in the manifest entities that carry them, it is unclear what precisely would be meant by superfecundity. Only if there is some form of congestion of knowledge caused by storage cost, will society shed some pieces of knowledge as it acquires and selects better ones. Whereas this is surely true for an individual with a finite memory, it is less obvious for society's knowledge being the union of all knowledge stored up in memory banks, libraries, hard disks and so on. Yet through most of human history before the "Age of the Gigabyte," congestion was a reality; books were hugely expensive before the invention of printing, and while their price of course fell, they were still quite costly by the time of the Industrial Revolution. Other forms of storage outside human memory banks such as drawings, artefacts in musea were all costly. Some selection may therefore have even occurred at that level. Moreover, in many techniques, knowledge drawn from storage devices may not suffice to fully define the set of instructions. So-called "tacit knowledge," a term coined by Michael Polanyi, plays a role in production. This part of the "how-to" instructions that form a technique must be learned from experience or from another person, and therefore the part of Ω underlying it is subject to congestion and thus to selection. More sophisticated technology transmission may reduce the ratio of tacit to formal knowledge that can be transmitted through non-human devices. What previously required an instructor or actual on-the-job experience can now be viewed on videos or simulated on computers.

Yet selection and extinction in Ω are very different from natural selection. Certain views of nature are incompatible with each other so that some theories are rejected, but they do not necessarily become extinct in the technical sense of being inaccessible. Although, the humoral theory of disease is still understood today, it 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 destroy any trace of it. Copernican and Ptolemaic views of the universe reside together in Ω, though of course not in the same position.

Insofar that there is incompatibility between different subsets of Ω, people have to choose again (Durlauf, 1997). We need to distinguish between knowledge that is "widely accepted" and widely believed to be false. Absolutes are useless here since people believing in creationist science, and members of flat earth societies must be allowed for, even if we can define a consensus from which they beg to differ. A third group of beliefs about nature is in dispute, and clearly those who adhere to it will be the ones that map this knowledge into techniques. When the selection environment on λ is not too stringent, such techniques with different bases in Ω can coexist; Freudian psychiatry and anti-Freudian psychiatry are one example. Needless to say, a great deal of knowledge at any time may subsequently be refuted and yet at that time be accepted and play a major role in mapping into techniques. Ptolemaic astronomy was used in the voyages of discovery and the caloric theory of heat in the development of early steam engines. The set Ω must also be divided into "active" and "dormant" knowledge, while only the active one is mapped onto λ, a bit like "coding" and "non-coding" DNA. Again, a grey area makes such distinctions somewhat tricky. Advances in paleontology, improved understanding about the distances of other galaxies, or the properties of black holes are clearly at first glance dormant, but many dormant sections of Ω can become active given a change in the environment.[4] This is probably what we refer to when we speak of induced technological change (Mokyr, 1998b). We can thus subdivide Ω into four different cells in a little two by two table; whether knowledge is active or not, and whether it is accepted or not. The cell "not accepted" but "active" is far from empty, not only because some people may not share the consensus, but also because the very essence of prayer, magic and miracles is to beg exceptions of nature's regularities rather than exploit them.

Darwinian models need therefore to specify the exact mode of selection that is operating on the system. Three different types of selection are relevant. One is the standard neoclassical mechanism: techniques are selected according to whether they maximize some kind of objective function. This includes supply considerations (to select the techniques that work and that are the most efficient), externalities (techniques may have strategic complementarities or incompatibilities with other techniques), and demand considerations (what does the market want). But it will, if all works well, produce economically efficient solutions if they are the only ones to work. A second type of selection is what may be called hysteresis. In any Markov chain we can build in as much inertia and irreversibilities as we want. In biological evolution a camel cannot change into a zebra once it discovers that zebras are more suitable to a given environment. In technological evolution these changes can and do occur, but they do so at a cost, often quite high. A third type of selection occurs at a social level, much like the social constructivists predict. At many levels, political power and lobbying, motivated by self interest, beliefs, prejudice and fear enter upon the selection process and direct it in one direction or another. Such a model could, of course, be incorporated into the objective functions and reduced to “what does the market want?” but it seems instructive at least to distinguish between criteria that relate to the actual functioning of a technique and other characteristics. For instance, non-Western societies might reject a technique developed in the West not because of any of its intrinsic characteristics but because it originated in the West. At a lower level, selectors may choose a technique through trust, conformism, tradition and so on. These are not necessarily just information-saving devices, but may reflect a variety of preferences, from resignation to the dictates of nature to religious beliefs that certain techniques are bad (e.g., Christian Science).

There are many issues in technological history that can be re-explored in this manner. For instance, does technological change occur in a gradual manner as Leibniz, Marshall and the neo-Darwinian phylogenetic gradualist orthodoxy in evolutionary biology hold, or can it move in bounds and leaps as Eldredge and Gould insist? The debate parallels those in economic history between scholars who believe in the Industrial Revolution and the great discontinuity it constituted and those who would deny it. 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? It is also crucial to re-explore the connection between the history of science which provided part of the “underlying structure” (in biology: the genotype) and the “manifested entity” (in biology: the phenotype). In what sense can we think of progress even if any simplistic notions about Panglossian outcomes are patently ahistorical? In what follows, I shall take a look at why and where innovation occurs at all, and whether that should surprise us. In particular, I would like to suggest here that small groups such as minorities, elites or small cities in predominantly rural societies have a crucial role to play in technological advances.

It should be emphasized that in all evolutionary systems, including technological ones, there are considerable inertia and constraints on change. One obvious observation is that because of the dynamic structure of evolution, in which knowledge depends on past knowledge, technical innovations (i.e., additions to λ) are likely to be an extension and modification of existing techniques. Yet, localized learning runs into diminishing returns or dead-ends, and for sustained technological advance to occur, bold and radical departures need to take place. I have referred to such departures as “macro-inventions,” a term that describes less the impact of an invention on the economy as a whole as much as the relation of knowledge incorporated in the invention to the rest of the knowledge currently in existence and in use.

The idea of macro-inventions is akin -- but not identical to -- the notion of speciation in biology. Speciation is the emergence of a new category of life that is distinct from everything that existed before. Such distinctions are often hard to make because of the grey areas between the categories. This is even true in biology: the distinction between species is based purely on reproductive isolation that is not a binary variable. In any event, biological distinctions are rather more arbitrary in higher genera. However, in most dynamic systems satisfying the criteria above, we do recognize a different type when we see it, and we have an intuitive notion of the distance even if this is hard to specify. Thus we realize that zebras are different from horses but that the difference between them is less than between a zebra and a cockroach. DNA analysis can nowadays quantify these metrics, but they were intuitively clear long before. Similarly, Catalan is different from Portuguese but closer to it than to Urdu. In the history of technology we can readily distinguish such categories although there is an inevitable area of inaccuracy and subjective judgment in such distinctions. Yet few would quibble with the statement that a four-stroke engine is different from an electrical motor, but closer to it than to a toothbrush.

My point is that macro-inventions are inventions that start the emergence of a new "technological species" or "paradigm." Insofar that the notion of these groups or classes is arbitrary, the distinction between macro- and micro-inventions, which I first advanced in 1990, can also be criticized as arbitrary. While correct, this does not obviate their usefulness. After all, historical analysis cannot proceed unless we try to find similarities and distinctions between phenomena.

One useful way to think about the economic history of technological progress is in terms of evolutionary trajectories that begin through a sudden novelty or macro-invention, and which are continuously improved and refined through a multitude of micro-inventions. These refinements eventually run into diminishing returns and asymptote off, at which point stasis is likely to occur until "punctuated" by a new macro-invention. It could be said that micro-inventions occur within an existing technological paradigm and are part of "normal technological change" whereas macro-inventions require a stepping outside of accepted practice and design, an act of technological rebellion and heresy.

It is not my contention that *every* technological tale can necessarily be reduced to this simple dynamic story. There are times, for instance, that the macro-invention proceeds through a few discrete stages. In some cases, such as the sailing ship and the water wheel, refinements were resumed and accelerated for a while after the technique had seemingly asymptoted off. But, by and large, whether we are looking at power technology, chemical engineering, information processing, medicine, the metallurgical industry, or even textiles, this type of dynamic seems a reasonable characterization of the history of useful knowledge. It raises the stakes in understanding where macro-inventions come from much like biologists are still eager to understand the conditions that lead to speciation. I propose, rather than attacking this question head-on, to examine a somewhat more manageable question. Under what conditions and in what kind of environment are major departures from and rebellions against existing useful-knowledge more likely to occur, all other things equal? Could one use the experience of the West to test whether rebellion is more likely to occur in comparatively small and relatively closed communities such as early cities and brought about by small compact groups living in them such as minorities, foreigners, and families of rich merchants?

3. Why and How innovations Do or Do Not Occur

For whatever reason, some evolutionary systems change rapidly and frequently while others remain in stasis for very long periods. In biology we sometimes observe periods of very rapid change known as "adaptive radiation." It might be tempting to think of exogenous agents, such as "mutagen" that somehow affect the rate at which novelty occurs. In biology, mutagens have been well identified as chemical and physical agents that disrupt the DNA copying processes. But, in knowledge systems the creative process is quite different and it is far more difficult to identify these "mutagens." Although the concepts, mutation and recombination, may be identifiable, the process is quite different. However, a property shared by all evolutionary systems is that their rate of change depends not so much on their ability to generate innovations as such but for those innovations to be selected and to become part of the set of manifested entities.

This is particularly true when it comes to the creation of new entire groups of entities. The ruling paradigm, based on extensive evidence in evolutionary biology, states that speciation is most likely to occur in relatively small, isolated populations. This is Mayr's (1970) concept of *geograhpic (allopatric) speciation*, in which speciation occurs when a subset of a population is isolated from the main body and reproduces with each other, eventually and gradually producing genetic variability. This kind of phenomenon has no precise counterpart in cultural and informational evolution, and at that level of abstraction, arguing for analogy is plainly false. But it is important to realize that the genetic structure of living beings is what I will call an inertive mechanism, 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 turn into what Kauffman (1995) termed the hypercritical region. In biology the resistance shows up first in the absence (or extreme rarity) of anything that resembles a Lamarckian mechanism. If Lamarckian change could occur, the rate of change of an evolutionary system would accelerate and stability would be unthinkable.[5] While genetic cohesion has not precluded the well-known adaptive radiations which created different species, these explosions of variety are little more than ad hoc variations. This cohesion, as Mayr emphasizes, 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).

This type of resistance also exists in knowledge systems and therefore in technology. They are 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 these suggestions are rejected, the cost of continuous experimentation and change would become infinite and the system would turn into complete chaos. However, even for unequivocally superior techniques, resistance is likely because of the finiteness of the number of techniques in use. In knowledge systems, existing techniques are embodied in agents using them, and these agents operate as intentional and rational agents. One can readily think of situations in which these agents will sustain losses if the new techniques are adopted 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 certain paradigms which, through our mapping functions, leads to conservatism in techniques as well. Had Einstein's notions that "God does not play dice" prevailed, much modern electronic technology might have been held back. Yet, when there are few direct interests at stake, and persuasion devices e.g., mathematical proof, statistical significance, and experimental evidence are well-developed and widely accepted, resistance to new knowledge about nature tends to be short-lived and moribund.

Every act of major technological innovation, then, is an act of *rebellion* against conventional wisdom and vested interests, and thus will normally lead to some kind of resistance.[6] Technological success occurs when the resistance fails to suppress the rebels, and they eventually become firmly established and even entrenched as the next status quo. Technological resistance has a number of different sources and mechanisms but it is a property of *all* evolutionary systems. Consider language; neologisms, grammatical errors and spelling mistakes are weeded out mercilessly by the red pencils of English teachers and copy-editors. Nevertheless, new words and usage, forms of spelling and even grammatical rules do eventually make it through, otherwise languages would have remained immutable over long periods. However, only a tiniest fraction of them ever have a chance, and of those another very tiny fraction gets selected. My point is that innovations (like mutations) can be explained either by the probability of one occurring at all or by the receptivity of their environment to them. In what follows, 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 have exact counterparts in evolutionary biology nor should we expect there to be any; what matters is that there is resistance to change, particularly to change that is drastic and sudden, altering the structure on which production and distribution rest.

1. *Economically motivated resistance*. Groups in the economy may resist changes in technology because they 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, but many others can be imagined as well.

2. *Ideologically motivated resistance*. These include various sources of political resistance that are not fueled by direct economic motivation, for instance, 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 function on low probability catastrophic events. Much of the resistance to nuclear reactors 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 resistance is to adopt an ideology of *conformism* in which deviancy -- whether technological, political, religious or ethnic -- is actively discouraged.[7]

3. *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 power could be made that solved the problem of direction; electrical power could not become a widespread of energy transmission until the problem of cheap generation through self-excitation was resolved.

4. *Systemic resistance*. As long as technology consists of individual components that can be optimized independently, changes in individual techniques depends on innovations of other components only through the price mechanism. In other words, a change in a particular technique will drive up demand for complements and reduce it 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.[8] If the costs and benefits of the adoption of a technique depend on the technique's ability to match with existing components, the process of innovation must take this into consideration. Technological change in a system becomes a coordination game that 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, 1997). In our own age, network externalities (broadly defined) place serious limits on the degree and direction of technological changes. Any new technology will need either to fit in with the existing system or be able to create a "gateway" technology that will bridge it. Software has to be "Windows-compatible," electrical tools require 115 volts, car engines are constrained to gasoline and

diesel fuels. Such standardization problems can be overcome, but only at a high cost, which impose an effective constraint on new techniques, and constitute a source of resistance. Failures of this kind often lead to government intervention.[9]

5. *Frequency dependence*. In many cases, the rate of technological change and the rate of adoption depend on the number of users. Economies of scale (within a firm), external economies (among different firms), and learning by doing effects fall into that category, as do all models in which users imitate their neighbors through social learning. Frequency dependence plays a role in technological change when the benefits of an innovation are unclear, so that a user will look at what his neighbors do and emulate them, trying to save information costs. In a selection model of literary success, for example, one can easily write a model in which more books are published than can be read by the population. Readers select books by relying on advice from friends and neighbors. Clearly, the more people who have read a book, the more likely it is for that book to be read by even more people. Some books become best sellers through little more than historical accident. Systems with these properties do not necessarily resist change; indeed, some of them do nothing but change, but their change tends to follow a given trajectory and resists moving to an alternative. They are classic examples of path dependence; where the system ends up depends on the particular path it has traveled and not only on its parameters (David, 1997). Network externalities are often the cause of positive frequency dependence (i.e., the likelihood of fax machines to be purchased depends on how many people already have one), but the two are not conceptually identical. Frequency dependence occurs in systems with positive feedback (Arthur, 1994); it means that it is often difficult to break into a market with a new product if there is no name recognition or there are no service networks. Frequency dependence can designate that one technique entirely drives out another (as in the case of VHS and beta), or allow the survival of a technique in a niche (such as two-stroke engines) but it normally implies a high entry cost. It therefore implies resistance to novelty.

In short, resistance to the “new” exists at various levels, and if innovations are to occur at all, they have to overcome these barriers. Innovation should thus be regarded as a two-stage process. First, will the new technique be permitted to compete at all? If it overcomes this resistance, it will be tested on the merits of its own traits. The question that needs to be asked is not: “why is there no more innovation” but “why does innovation occur at all, and how does it succeed in overcoming the first stage barriers?” There is no single answer to that question, of course. There have been inventions in history, so 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 “macro-inventions” by the standards described above. Among the nineteenth century inventions, the telegraph and x-ray photography were of that nature. These advances share the feature that the improvements in the desired traits were easily verified and impossible to dispute. 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 are quite different). Is such resistance normally more easily overcome in compact or large communities; in open or closed ones?

The concept of a community here is not identical to the political unit, and I do not wish to suggest that for that reason small countries have an edge over larger ones. Communities can be subsets of national units or transcend them. A minority group, living in its own geographical or social ghetto, would be defined as a community. A community is the unit in which the fate of a new technology is decided. Are small communities, those that are "geographically isolated" to use Mayr's concept, more likely to overcome resistance than large communities in the same way that small groups are more likely to spawn successful new species? On a priori grounds, it could be argued either way. There are economies of scale in research and development; large markets create more opportunities to cover the fixed costs of increasing the knowledge base. All the same, I would propose that, by and large, an analysis of the *sources of resistance* distinguished above suggests that relatively small units -- properly defined -- would have an edge over larger units. However, this is strictly a *ceteris paribus* argument; there are many factors involved in the creation and implementation of new useful knowledge and size is only one of them.

The first cause of resistance, the *political lobbying of vested interests*, is clearly size-dependent. The reason is firmly rooted in the logic of collective action; it is easier for small groups to organize than for larger groups because the costs of detecting and punishing free riders goes up with the size of the group. The benefits of innovation are normally distributed over a large population of consumers and hard to organize for collective action, while the costs of technological progress are often concentrated among a comparatively small number of producers in a trade association, guild, or even town. One, rather oversimplified, way of looking at the success of technological progress to overcome resistance is to examine this as a political struggle between consumers and potential losers. The condition for size to be an effective determinant of the efficacy of resistance to technological change is simply whether the cost of organizing consumers falls faster with size than the cost of organizing affected producers.

Perhaps more relevant is the fact that small economies tended, all other things equal, to be more open to the rest of the world than larger units. Although there are notable exceptions to this rule (North Korea and Myanmar today; Albania before 1992). But the historical experience up to 1945 would point to the United States, Russia and China as large economic units with a comparatively small proportion of their GNP exported, while most small economies tended to be more trade-oriented. In large part, this is simply the consequence of the trivial fact that larger countries are more diverse and thus have less need to depend on foreign trade. It has, however, an unexpected benefit; political restrictions on new techniques are less effective in open economies (Mokyr, 1994b). It is more difficult to keep producers in open economies from using new techniques developed elsewhere, as they are competing with producers not subject to restrictions. Hence it is not size as such that matters here, but its correlate -- openness. The effect, however, is quite similar.

The *ideological element in the social resistance* to innovation works quite differently. Openness to the rest of the world makes it more difficult for technologically reactionary lobbies to use non-market mechanisms to put obstacles in front of innovation. Small, compact societies are not invariably progressive. Ethnic or religious groups and minorities, even if they were always forced to interact with the world around them have, at times, displayed a stubborn ability to stick to their own conservative ideology, of which the Amish are perhaps the most prominent example. The history of the Jews points in the same direction; Jewish traditions have usually been backward looking and focused on tradition, precedence and exegesis of existing wisdom rather than rebel against it as invention demands. The tolerance of its society to the non-conformist and the innovator has been low. It is therefore not surprising that the contributions of Jews to the history of technology before 1850 were negligible, a fact all the more striking because of the high standards of literacy and education prevalent among them. At the same time, very large empires such as Rome, China, the Ottoman Empire, and Russia have been victims of cultural arrogance spawning a "not-invented-here" attitude and regarding foreigners as Barbarians -- a common form of technological resistance.

The third cause, the *strategic complementarities* effect seems to work squarely against "smallness." After all, if someone invents technique 'A' which can only work if complemented with technique 'B', the larger the community (or the minority) in which the inventor operates the greater the chance that he or she will find the right complementarity or someone who can produce it. While this is a function not only of size but also of the diversity of the community and its openness, by itself this element seems to counteract smallness. But such a notion ignores the fact that information flows are themselves a function of size. Depending on the particular way information is exchanged in a network, size can be an advantage or a disadvantage. While usually there are economies of scale in information networks, it is possible to imagine a small community where people interact more intensely and know more about each other, even if they have contact with fewer people. Dependent on the technology of communication, the flow of information may depend on size, density, or some combination of the two. The net effect of size, in such an environment, is indeterminate. As I will discuss below, relatively compact, dense units such as cities may have been optimally sized for technological advances.

Network externalities, by contrast, are strongly correlated with size. Some network technologies tend to help *create* larger communities (e.g., the effects of railroads and automobiles on market integration). Almost by definition, introducing an incompatible technological element into an existing system is more costly, the larger the system. Especially when the system is defined as a standard that has to be altered, inertia seems rather unavoidable. However there are at least two complications that make the relation more complex and ambiguous. First, it is unclear whether the significant element is total or per capita costs. Second, system incompatibilities can be resolved by creating gateway techniques; the higher the costs of systemic resistance to a novel technique, the higher the payoff to the development of such gateways.

Finally, *frequency dependence* seems to point firmly in the direction of advantages of smallness. In general, smaller societies are more flexible when it comes to changes in highly interdependent and coordinated equilibria. If, for instance, production costs are a monotonically declining function of aggregate output (cumulative or not), these costs would be higher in small communities which would imply that existing techniques are more deeply entrenched and more difficult to displace in large communities.

4. The City-State: An Assessment[10]

In modern economies, it is sometimes assessed that technological change is a conscious and deliberate function of the resources devoted to research and development. This view about technological progress is not wholly without its critics, but it surely is less true -- at least in the Western world -- before 1800. In the historical context it is far more useful to think of new technologies as successful individual acts of rebellion against a technological status quo. We rarely know the names of pre-Industrial Revolution inventors, but *somebody* must have defied a tradition and proposed novel things, from the mechanical clock to the blast furnace to the potato. If the evolutionary framework is to be of any use, it should predict that there is a strong connection between the social environment and its ability to overcome the built-in resistance to change and technological progress. In what follows I look at a specific instance of such a relationship, namely the nexus between cities and technological progress before the Industrial Revolution.

Traditionally, cities have been classified into commercial, industrial, or administrative and ecclesiastical centers and many served as some combination of all three functions. It may be useful to add the observation that many successful European commercial and industrial towns were, by and large, politically independent units, with a high ratio of urban to hinterland population and with almost no dependency on a larger state. By contrast, the metropolises that were parts (often capitals) of large states or empires had economies that were, to a large extent, ancillary to the needs of the bureaucracy, the military, and the luxury demand of courts. The first difference that comes to mind when comparing, for example, Florence with Paris, or Hamburg with Vienna is not just their function but their political status. This distinction, too, suffers from the pitfalls of a dividing line along a continuous variable. Important city-states like Carthage, Amsterdam, and Venice controlled, in their zenith (or after it), fairly substantial territories, while the amount of territory controlled from Copenhagen was rarely very large. All the same, if the hypothesis that urban centers were a causal factor in bringing about technological change is true, it would be especially so for city-states where economic activity was less subservient to the political and dynastic interests of empires.

The traditional city-state, an institution that emerged in antiquity and that has shown a remarkable resilience over time is supposed to have been, above all, a trading center. The late Sir John Hicks (1969), in his remarkable little book on economic history, was one of the first economists to draw our attention to the city-state and defined its core as “a body of specialized traders engaged in external trade.” Rosenberg and Birdzell (1986) followed him in this line of thinking. Whether we think of the Phoenician and Greek towns before Rome, the medieval Hanseatic towns, or the Dutch Republic in its golden age, the first association we have is one of Smithian growth supported by unique institutions defending property rights.[11] Ethnic and religious minorities played important roles in commercial development in Europe and Asia. Through connections with their kin overseas, they maintained networks that were essential to information flows and contract enforcement. One example of such a minority is the community of Maghribi traders in early medieval Mediterranean trade, as described by Greif in his classic paper (1989).

How much evidence in European history is there to support a correlation between the special process of urbanization and commercialization that produced city-states and technological development? The exact connection between Smithian growth (due to gains from trade) and Schumpeterian growth (resulting from shifts in production capabilities) are complex and still the subject of dispute. Scholars, writing mostly about the modern period, have had few doubts.[12] In the medieval East there were large towns, great centers of civilization, above all Constantinople, but also Baghdad, Edessa, Aleppo and Alexandria. Yet these towns, precisely because they were parts of larger political units, made only modest imprints on technological innovation.[13] By contrast, Italian city-states in the early Middle Ages began a growth process due to technological progress as well as to their role in reviving international trade (the glassblowing industry of Venice was clearly the central pillar of their prosperity before they began to dominate the eastern Mediterranean trade).[14] Other Italian towns led the world in innovations in fine textiles, in metalworking, in the use of chemicals, and later in printing, clock making, optics, cartography, and instrument and gun making. One historian, after describing the technical advances of the Italian Renaissance, concludes: “these alone made its opulence possible” (Hall, 1967, p. 85). The case for a technologically driven city-state could also be made for the medieval Flemish towns, which were able to adopt the new textile technologies in cloth making in the early Middle Ages and formed what is probably the first purely industrial-urban complex in the thirteenth century. It is not fully understood, however, why by the eleventh century this industry was so heavily urbanized, and whether the pivotal innovations in textile industry like the spinning wheel and the horizontal loom actually found a more hospitable environment in these towns. A better example is the contribution made by the instrument-making centers in Nuremberg, Augsburg and similar cities in southern Germany and Switzerland in the fifteenth and sixteenth century (Price, 1957). Antwerp was a pioneer in crystal making and sugar refining before its sudden demise after 1585.

Perhaps the economically most successful city-state of all times was the Dutch Republic.[15] In its heyday, the Dutch were not only at the center of a huge commercial and financial center, they were also the technological leaders of their age. Although there was no Industrial Revolution (in the standard definition of the term) in Holland, in the period between 1500 and 1700, the Dutch cities were at the technological cutting edge of the world. Although like any technologically creative society the Dutch adopted a substantial number of foreign inventions, they also generated a large number of original ones (Davids, 1993, 1995). A great number of Dutch inventions spread throughout the Western world. Their advances in shipbuilding technology (Unger, 1978) fed directly into their commercial prosperity, but there was much more; in textiles and in paper making, the two major advances of the period were the Dutch ribbon loom and the *Hollander*. The utilization of energy sources such as wind-power which was adapted to sawmills, and peat, widely used in all industries requiring fuel, were taken to new heights. The Dutch also led the world in hydraulic technology, optics, instrument making and made significant contributions to every other field, from clock making to medicine (de Vries and van der Woude, 1997). Within the Dutch cities, division of labor and external economies were at work, leading to technological specialization. Thus Gouda produced pipes, Delft produced the cheap decorative imitation chinaware named after it, the Zaan area specialized in sawmills. Scientists living in the Dutch cities made important contributions to “useful arts,” that is, technology. The Dutch scientist Christiaan Huygens invented the clock pendulum, and the mathematician Simon Stevin invented the decimal point -- both economically important breakthroughs. Huygens’s assistant, Denis Papin, was credited with building the first working prototype of a steam engine. The paradigmatic inventor of the age was the engineer Cornelis Drebbel (1573-1633), born in the town of Alkmaar, who has been given credit for the invention of the microscope, built a prototypical submarine, and made many important improvements to furnace making, metallurgy, clock making and chemicals.

It is easy to think of reasons why technology in this period developed faster in cities than in the countryside. It might be thought that commercial success in and of itself would stimulate technological creativity and that the same institutions that fostered trade also fostered invention. International trade provided producers with access to expanding markets as well as encouraged innovation in industries that were directly ancillary to trade such as shipping and packaging. This kind of link in its simple form is little more than a variant of the fallacy that necessity is the mother of invention, and there are enough exceptions to this rule to make most generalizations questionable.[16] It seems reasonable to surmise, however, that if cities in earlier stages of their development depended on commercial success leading subsequently to technological advances, their history may be regarded as a mechanism of long-term economic growth. By fostering urban growth, those elements (such as minorities, commercial elites, and immigrants) that made commercial success possible eventually helped create the niches and environment within which technological change had a better chance to overcome the forces of conservatism. We need to specify what drove the technological advances in the first place rather than the specific direction they took. Successful invention feeds upon the exchange of ideas across different fields, a sort of technological recombination, where ideas from one field are transplanted and adapted to others. Urban areas, because of the higher frequency of human interaction, were clearing houses for ideas and information, and so invention was facilitated further by the continuous interface of different types of knowledge. The inhabitants of cities, moreover, also had more contact with foreigners, as the cities were nodes of travel and communication.

Equally important, successful invention depended on the existence of two complementary elements: the original idea, and the skills and workmanship to turn the idea from blueprint into model and from model into successful products. High levels of skill tended to exist largely in urban areas because of the possibility of finer division of labor. Clock and instrument makers, fine gold and silversmiths, skilled carpenters and cabinet makers, fine leather workers, opticians, and similar skilled craftsmen as well as mathematicians, pharmacists, and alchemists, were instrumental in providing the workmanship and materials on which innovators depended. In towns it was easier to find the skilled artisans and engineers that could transform a technological idea from blueprint to reality. A long and venerable tradition in economic history, beginning with Adam Smith has maintained that the division of labor and specialization themselves bring about innovations, although the matter has remained controversial.[17] Literate people resided in towns, and eventually they became the sites for institutes of higher learning, libraries and the residence of scientists. Cities have been considered to be, on the whole, more amenable to innovations because "the urban milieu provides a natural refuge for original spirits ill at ease in rural areas, where the pressures to conform is as a rule stronger" (Bairoch, 1988, p.336).[18]

Furthermore, size alone provided the city with a more competitive environment simply because the consumer was not restricted by distance to a single or small number of suppliers. This advantage, however, was at times negated by the formation of cartels. Some inventions required a critical mass of nearby customers and thus areas of high density, e.g., the medieval mechanical clock, first constructed as part of urban churches.[19] Finally, we too often think of technological diffusion as mere information flows. What is often overlooked is how much *persuasion* is involved in the process of technological diffusion; innovators need to persuade customers of the value of a new product, lenders of their creditworthiness, and the authorities of their loyalty. Especially when the traits of the new technique can only be verified upon actual production and consumption (and when there is "frequency dependence"), the new technique must be given "a chance." Informing someone that an innovation has been made is still a distance away from making him or her willing to buy or finance it. While the success of persuasion effort is naturally an idiosyncratic matter, it seems plausible that this kind of discourse was naturally simpler in towns if only because innovators could choose from a larger number of individuals.[20]

Perhaps the most direct test of the hypothesis is to compare the technological creativity of compact city-states to the innovativeness of cities that were parts of much larger political units. The differences between city-states and cities such as Madrid, Rome, St. Petersburg, Vienna, and even London that were part of larger political entities were a matter of degree. Empires, however, almost always had a political or dynastic interest to which the mercantile and industrial interests were sacrificed if necessary. Taxes may have been higher or lower in imperial cities, but they were spent on items that did not always coincide with the economic interests of the town. More important, empires, whether they were centralized or not, were normally less tolerant to rebellion than smaller units. They demanded obedience and conformism at a level far higher that could be expected in smaller units. France, Spain and the Empire all resisted the greatest rebellion of them all, the reformation of the sixteenth century. While Protestants did at first not prove to be much more tolerant, of course, they eventually became so. The fact remains that in smaller and mostly urbanized political units this "religious mutation" succeeded, whereas in the Habsburg and Valois-Bourbon monarchies, it failed. Technological rebellion is different from religious heterodoxy, and the correlation between them is a matter of a complex literature. Conservative large units would be suspicious of either religious or technological heterodoxy, equating heresy with rebellion, and probably more able to thwart them than in the more compact societies of city-states.[21] Moreover, luxury demand by rich and lavish courts rarely spawned much innovation and had a large import component. By and large, imperial cities diverted resources and talents into non-technological channels such as administration, the military and religion. At times, these sectors were correlated with technological advances as well (e.g., in architecture or garden design), but, on the whole, the imperial cities' contribution to new technology was small in proportion to their population and by comparison with the independent or quasi-independent city-states. This evidence about cities may be the most clear-cut difference between large and small units and the best example we have in economic history for some isomorphism to Mayr's allopatric processes of speciation.

Much like the processes of spasmodic leaps and bounds we observe in natural history, technological advances appeared in periods of feverish outbursts, known as punctuated equilibrium processes. Societies that have been technologically creative have tended to be so for relatively short periods. Some urban economies such as sixteenth century Antwerp were devastated militarily before they reached this stage, but those that, like Venice and Amsterdam which survived deep into the eighteenth century had lost, by all accounts, their technological creativity and dynamism long before their demise. Thus, external and internal elements worked to bring about similar consequences. In general, economies that were technologically progressive were not able to maintain their dynamism for extended periods. In previous work I have termed this historical regularity "Cardwell's Law" (Mokyr, 1990, 1994b), in honor of the eminent historian of technology, Donald Cardwell, who first observed this phenomenon.

What accounts for Cardwell's Law? One possible explanation stems from the framework set up by Olson (1982) who posits convincingly that over time such institutions tend to become ossified, riddled with stymieing regulations and rules, rewarding rent seekers rather than innovators. Eventually they become hostile to technological progress and stifle economic growth. These regulations were aimed at maximizing the wealth and welfare of the members of the association, operating as a cartel and strictly limiting entry and quantity of output. It is perhaps inevitable that sooner or later the existing physical and human capital of the members will become an object of political protection, implying that almost all innovations will be resisted. Each society is ruled by a technological status quo, a particular set of techniques embodied in human and physical capital. Changing technology tends to devalue these assets, and thus their owners try to resist technological change and, if possible, stop it altogether, even if their own wealth rests on a successful rebellion against an earlier technological status quo (Krusell and Rios-Rull, 1996). Alternatively, one can assume that existing cities have a great deal of experience with an existing set of techniques and find a radically new technique which requires a great deal of experimenting and learning, costlier than an old and known one. This implies that when a macro-invention radically changes production technology, it is likely to take place in a new site while the existing city stays with the old technology (Brezis and Krugman, 1997).

In pre-modern urban Europe the bodies that enforced and eventually froze the technological status quo in urban areas were, above all, the craft guilds which resisted the new techniques and consequently many urban economies eventually entered periods of technological stasis. There are many examples of guild resistance to change, analogous to the kind of resistance that occurs in other evolutionary systems.[22] The traditional literature is unambiguous about this phenomenon (see Pirenne, 1937). In city-states, craft guilds usually had enough political influence to impose their will on the rest of the community. In other cities, they often became a tool of the monarch in controlling and taxing the city, in exchange for royal assistance in protecting the economic interests of the status quo.

Nevertheless, their impact on technology should not be regarded as pervasive, and even less as uniformly negative. One element limiting their effectiveness was the natural division of labor between town and countryside. Much of the industrial technology before the Industrial Revolution developed in the countryside for geographic reasons; around rural sources of energy, minerals, and cheap labor, but some of the production moved to the countryside to get away from the guilds' sphere of influence. Some of the new technologies to emerge in early modern Europe were inevitably rural: wind-power, water-power, and charcoal for iron smelting. But some inventions could be operated in worker's home, in the countryside or just as well in cities: the new spinning wheels and the horizontal looms, which appeared in the eleventh and twelfth centuries. For centuries, the textile industries of the Flemish and Toscan towns competed with their respective countryside. In part, this competition eventually resolved itself in symbiosis; the more advanced and sophisticated parts of the work were carried out by urban artisans, whereas rural workers received from putting-out entrepreneurs the simpler jobs.

The role of guilds was particularly interesting because they stipulated a mechanism by which skills were transferred across human generations, from master to apprentice. In a recent paper, Epstein (1998) has shown that this was one of the central features of the guild systems, and that its long survival was a function of these technological activities. By setting up standards for training and practices they guaranteed the smooth transmission of skills and technological expertise from one generation to the next. They may have helped to avoid the dangers of under-investment in human capital that are part of any training system in which general skills are being taught at a cost to the instructor. Epstein also maintains that guilds served as a mechanism for the establishment of intellectual property rights in new technology. If his arguments in defense of the technological progressiveness of craft guilds are correct, it would establish another link between urbanization and technological progress in medieval and early modern Europe.

It is clear that such a system lends itself well to a *crystallization* of technical knowledge in which masters transferred a fixed and immutable body of knowledge with the authority, making rebellion and deviancy against it very difficult. A linear system of vertical transmission of knowledge is far less flexible and open to innovation than one in which technological information was transmitted through a multiplicity of channels. In some cases the social life of the guild was instrumental in the kind of information exchange that was required for recombinant technological progress. The role of guilds -- which survived as an institution for over half a millennium in Europe -- was sufficiently complex and variable to sow seeds of reasonable doubt among some economic historians as to their long run effect on technological progress.[23]

The physical proximity of urban residents to each other made the kind of organization we associate with medieval urban guilds possible. In cities the usual free rider problem that thwarted the success of special interest coalitions was less severe, as the compact size made monitoring easier. In any event, the city government could be relied upon to enforce the rules and regulations supported by the guild; enforcement was cheaper in small and densely populated areas. If and when guilds were progressive agents, the cities' progressive elements benefited; when they became more conservative, technological decline ensued. The effect of cities on technological development is thus made ambiguous by the dialectical nature of technological progress in which success creates the seeds of conservatism and the tendency of successful loci of technological creativity to degenerate eventually into stagnation. This dialectical nature is inherent to all evolutionary dynamics. Change begets more change, but eventually negative feedback will come to dominate positive feedback.

To be sure, the tendency toward technological stagnation was kept in check by the wholesome effect of the forces of competition. Cities that refused to adopt certain innovations found themselves in positions weaker than those that had accepted them; the crystallization was rarely complete. Davids (1995) and Epstein (1998) demonstrate that despite institutional rigidities and guild resistance, cities were not altogether immune to innovators. Urban craft guilds resisting innovation ran the double risk of competition with other cities and with their own countryside.[24] The European city-state was part of what Jones (1981) has termed the "states system" which provided European society with enough inter-society competition to facilitate the long-term economic growth experienced by the continent.[25] All the same, the states system worked primarily for Europe *as a whole*; while the effect to *individual* political units as a result of the states system is less clear. Economies of scale in military organization suggest that city-states, in the long run, had difficulty keeping up with more powerful if less progressive states. As a consequence, the same states system that facilitated the long-term survival of technological creativity in Europe led to the demise of many of the most creative units through a long sequence of sieges, ransacking, and plundering. The prosperous and creative towns of northern Italy and the southern Netherlands were, in the long run, no match for the armies of Spain and France and the great centers of Germany and France were devastated by the religious wars between 1572 and 1648.

In short, historical evidence and theoretical considerations borrowed from the theory of evolution suggest that city-states may well have been a source of technological creativity during much of Europe's history, but that there were powerful forces limiting their advantages. Although the net result is indeterminate and varied over time and space, and despite a number of indisputable triumphs, city-states were a precarious and often unreliable reed to lean on for sustained technological progress. Between the internal threats of vested interests and the external threats of war and subjugation by stronger military units, urban innovativeness maintained an uncertain and short-lived existence. The contribution of the totality of all European urban centers taken together, however, was enormous even if each individual unit's contribution was only for a limited period.

5. Conclusion

This chapter has suggested that evolutionary frameworks may be useful in rethinking old issues in the creation and diffusion of new technological knowledge in historical contexts. In understanding long-term economic growth, we need to establish the kind of environment in which the technological equivalent of speciation can occur. This chapter has emphasized that technical innovation is an act of rebellion against conventional wisdom. In order to understand how technical changes occur, it is then necessary to analyze the sources of resistance.

I have proposed that, among many other factors, the actual size of the "community" is relevant. Any area that is relatively compact (such as a city) may have an advantage on larger, more spread-out communities. Inside the city, minorities have eventually helped create the niches within which changes had better chances to overcome the forces of conservatism. This means that the city-state, with its unusual ability to tolerate minorities and foreigners, its openness to the world and its relatively efficient flow of information, may have had an advantage on other geographical configurations.

An evolutionary perspective that focuses on the resistance faced by an innovation in a generally conservative environment predicts that, all other things equal, communities are more likely to be the loci of technological progress. The role of minorities in the development and diffusion of technological progress is ambiguous. On one hand a minority, with the characteristics of a community, can be more prone to overcome resistance. Small units would have an edge since they display less resistance than larger units; they are easier to organize and are less prompt to vested interests. On the other hand they can display social resistance. Some minorities stick to their own conservative ideology, and their tolerance to the non-conformist and the innovator can be low. It is not clear if minorities have some advantage in technical innovation but even if they had some, it probably would not persist, since technological creativity is of relatively short duration.

Notes

* This chapter is based on my book *Neither Chance nor Necessity: Evolutionary Models and Economic History* (Princeton University Press, forthcoming).

1. 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).

2. See Mokyr (1991, 1996, 1999).

3. 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).

4. By "environment" in this context I mean not only the physical environment in which the technique operates but also the development of complementary or rival techniques that may lead to the activation of previously dormant knowledge. Indeed, such processes are what constitute "adaptation" in all evolutionary processes.

5. I am indebted to my colleague David Hull for this insight.

6. 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 (1994a, 1998a).

7. Conformism also means that new knowledge will be resisted unless it fits into an accepted paradigm. In other words, the mappings from Ω into λ introduced above provide a source of resistance. If a body of natural knowledge exists that for some reason is inconsistent with the implications of a new technique, this technique will be resisted particularly if it does not have a strong base in Ω. For example, when quinine was first

introduced into Europe, it was resisted for a number of reasons, one of them being that it did not mesh with accepted Galenian practice. However, the germ theory of disease by the late nineteenth century confirmed and strengthened accepted practices by Sanitarian movement, and as such was relatively easy to accept by the medical establishment (Duran-Reynals, 1946, pp. 45-53). 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 results can be readily demonstrated, as was the case with smallpox inoculation. In most 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 acupuncture, astrology, mind-reading and other techniques not firmly based on an accepted part of Ω are still regarded with great skepticism even if they are widely used. The same is true by the polygraph machine which relies on a questionable foundation in natural knowledge and the actual effectiveness, of which much like homeopathic medicine is controversial (Alder, 1998).

8. It is sometimes thought that "technological systems" in T.P. Hughes's celebrated definition did not come about until the Industrial Revolution (see, for instance, 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.

9. An interesting example of a network technology that now resists change is the use of Minitel computer terminals in France, heavily subsidized and encouraged by the French government which, a decade ago, was regarded as cutting-edge technology. But according to *The Economist* (May 2, 1997, p. 18) "those inflexible Minitels are still in use a decade later, while the rest of the world has embraced the advantages of networking through the Internet. France, once a leader, now lags behind."

10. The following is adapted with substantial revisions from Mokyr (1995).

11. The idea that the citizens of city-states enjoyed better and more secure property rights is an old one recently revived by DeLong and Schleifer (1993) who show that the freedom from arbitrary taxation in non-despotic governments was conducive to economic growth (and, in turn, to taxation). Using regression techniques, they actually venture to estimate the damage (in terms of population) to the urban populations of Europe by the emergence of an absolutist prince. Regardless of the question whether the taxation in city-states was higher or lower than in empires and whether they have fully accounted for the insecurity of property rights on account of external threats, their data demonstrate that there was something viable about the independence from absolutist rule in some regions of Europe. At the same time they ignore at their peril, as the following will show, de Vries's warning, "one cannot assume that incremental urbanization *necessarily* denotes incremental economic growth" (1984, p. 246).

12. Boserup (1981, p.77) has no doubts when she concludes (in the context of classical antiquity) that "urbanization was accompanied by rapid progress in the technology of construction, transport, and agriculture ... the need to organize the urban economies ... led to some of the most important inventions in the history of humanity." Bairoch (1991, p.160), writing about a more modern period, asks rhetorically whether the city has not had a considerable hand in stimulating invention and ensuring its diffusion and then states categorically that "there are few attributes of urban life that do not favor the diffusion of innovation" (*ibid*., p. 169; see also Bairoch, 1988, p. 327). Jacobs (1984, pp. 224-5) maintains that "cities are the open-ended types of economies in which our open-ended capacities for economic creation are not only able to establish 'new little things' but also inject them into everyday life" and elsewhere notes that "the huge collections of little firms, the symbiosis, the ease of breakaways, the flexibility, the economies, efficiencies and adaptiveness -- are precisely the realities that, among other things, have always made successful and significant import-replacing a process realizable only in cities and their nearby hinterlands" (p. 40).

13. Baghdad, for instance, was an important center preserving Hellenistic technology and funneling Eastern knowledge to the West. Paper entered the Mediterranean region (and from there Europe) through Baghdad (around 800), and it was there that the Banu Musa brothers published their great books on mechanical engineering (850). Nevertheless, Islamic technology, whether it lacked originality or not, ran out of steam quickly and was eventually outdone by the ingenuity of Western Europeans.

14. Strictly speaking, glassblowing was a Roman invention dating from the first century BC, but the technique fell into oblivion in the Western world until it was reintroduced into Venice from the Moslem world. Despite the predominance of merchants, by the tenth century glassblowers had made their way into the Venetian upper class. See Lopez (1971, p. 63).

15. There is a certain ambiguity here; the Dutch Republic was not so much a city-state as a loose confederacy between the urbanized maritime provinces of Holland and Zeeland, and the more agrarian provinces of the East and North. The city-state concept refers to Amsterdam and the smaller towns in its region (Haarlem, Leyden, Delft, etc.).

16. Both imperial Rome and Manchu (Qing) China are examples of systems dependent on Smithian growth in which technological achievements were modest by comparison. By comparison, some of the great inventions of early medieval Europe, including the horse collar and the three-field system occurred in societies in which commerce and exchange, both long and short distance, had declined to a trickle.

17. Landes (1993, p. 159n) points to the special skills of clock and instrument makers as evidence of Smith's view. Some of them played important roles in the invention of mechanical devices in post-medieval Europe. But, as a general statement, a connection between the kind of division of labor envisaged by Adam Smith and sustained technological progress is hard to demonstrate. For every example of clock makers or shipbuilders, we can find others where no such externalities existed. Specialization of an economy in sugar-cane growing or charcoal burning would not much enhance technological progress in seventeenth or eighteenth century Europe. Moreover, beyond some point further specialization which trains each worker to carry out only one-minute stage of the production process deadens creativity by separating the worker from the larger picture and deprive him or her from knowledge in other areas. Adam Smith himself (1976, pp. 781-2) stated that the cost of the division of labor was "that a man whose whole life is spent on a few simple operations ... has no occasion to exert his understanding or exercise his invention ... and generally becomes as stupid and ignorant as it is possible for a human being to become." Elsewhere, Smith (1978, p. 539) asserted (without providing any evidence) that an overly fine division of labor was responsible for the "low people [being] exceedingly stupid. The Dutch vulgar are eminently so ... the rule is general, *in towns they are not so intelligent as in the country, nor in a rich country as in a poor one*" (emphasis added).

18. Tolerance and pluralism have been widely regarded in the literature to be important elements in the environment fostering technological progress. Bairoch (1991) relies on contemporary evidence indicating that larger cities tend to be more tolerant of dissenters and deviants (Wilson, 1985). Whether historically this is true for Europe is unclear: for every case of tolerant and cosmopolitan Amsterdam or Hamburg, one can think of examples such as Savonarola's Florence or Calvin's Geneva. See also Goldstone (1987).

19. Hoock and Lepetit (1987, p. 22) draw an analogy between the medieval public clock and late nineteenth century telephones. The telephone, as it soon was extended to rural regions, also serves as a reminder that technological changes could easily negate the advantages in communication enjoyed by the inhabitants of urban areas. Sufficiently cheap transportation and communication eliminated commercial city centers in favor of suburban shopping malls and the latter may ultimately succumb to on-line Internet retailing.

20. Bairoch (1991) points out that in the diffusion of technological knowledge, the numbers matter; it is the probability of encountering knowledge of new inventions or having it that counts. In cities, these probabilities are higher because each individual meets on average a great deal more people.

21. The Catholic Inquisition, the most powerful body created to enforce conformism, actively pursued would-be innovators as "magicians" and discouraged innovation in Catholic southern Europe. See Mokyr *(*1990, p. 76).

22. For the wool industry in medieval England see Carus-Wilson (1952, 1966). For the Low Countries, see, for instance, Van Uytven (1971). For other examples from industries as far apart as shipbuilding and printing see Unger (1978) and Audin (1979).

23. Hohenberg (1992, p. 167) feels that the picture of guilds resisting competitive forces and change "cannot be even remotely accurate." Though he is correct that it is implausible that guilds were willing to court economic ruin rather than sacrifice their short-term interest, even the guilds controlled by the corporate mercantilist state could be a serious impediment to technological change, as was the case in *ancien régime* France. See, for instance, Deyon and Guignet (1980). Clearly, Hohenberg's statement that guilds were a tool controlled by urban elites to impose stability on the cities is consistent with the argument made here.

24. The Dutch Republic, a confederacy of semi-autonomous city-states, was fortunate in that legislation was local and uncoordinated. Thus, when the Leiden ribbon makers guild objected to the newly invented ribbon loom in 1604, the city authorities declined the request to ban it out of fear that the industry would migrate to Delft where the guild was less conservative (t'Hart, 1993, pp. 117-8).

25. A good example of the operation of the states system is the decline of the old urban woolen centers in England, Italy, and Flanders in the fourteenth and fifteenth centuries. These centers, where competitiveness was increasingly weakening due to a frozen technology were losing ground to smaller towns "where vested interests and conservative forces were less strong" and where technological creativity was able to meet the challenges of the new products and means of making them that appear in Europe after 1350 (Carus-Wilson, 1952, p. 428).

References

Alder, K. 1998. "To Tell the Truth: The Polygraph Exam and the Marketing of American Expertise." Northwestern University: mimeo.

Arthur, W.B. 1994. *Increasing Returns and Path Dependence in the Economy.* Ann Arbor, MI: University of Michigan Press.

Audin, M. 1979. "Printing." In M. Daumas, ed., *A History of Technology and Invention*. Vol. 3, *The Expansion of Mechanization, 1725-1860*. New York: Crown, pp. 656-705.

Bairoch, P. 1988. *Cities and Economic Development*. Chicago: University of Chicago Press.

Bairoch, P. 1991. "The City and Technological Innovation." In P. Higonnet, D. Landes, and H. Rosovsky, eds., *Favorites of Fortune: Technology, Growth, and Economic Development Since the Industrial Revolution*. Cambridge: Harvard University Press.

Bauer, M., ed. 1995. *Resistance to New Technology.* Cambridge: Cambridge University Press.

Boserup, E. 1981. *Population and Technological Change*. Chicago: University of Chicago Press.

Boyd, R. and P.J. Richerson. 1985. *Culture and the Evolutionary Process*. Chicago: University of Chicago Press.

Brezis, E. and P. Krugman. 1997. "Technology and the Life Cycle of Cities." *Journal of Economic Growth* 2(4): 369-83.

Campbell, D.T. 1987. "Blind Variation and Selective Retention in Creative Thought as in Other Knowledge Processes." In G. Radnitzky and W.W. Bartley III, eds., *Evolutionary Epistemology, Rationality, and the Sociology of Knowledge*. La Salle, IL: Open Court, pp. 91-114. (Originally published in 1960.)

Carus-Wilson, E. [1941] 1966. "An Industrial Revolution of the Thirteenth Century." In E. Carus-Wilson, ed., *Essays in Economic History*, Vol. 1. New York: St. Martin's.

Carus-Wilson, E. 1952. "The Woolen Industry." In M.M. Postan and E.E. Rich, eds., *The Cambridge Economic History of Europe* Vol. II. Cambridge: Cambridge University Press.

Cavalli-Sforza, L.L. and W.M. Feldman. 1981. *Cultural Transmission and Evolution: A Quantitative Approach*. Princeton: Princeton University Press.

David, P.A. 1992. "Path Dependence and Predictability in Dynamic Systems with Local Network Externalities: A Paradigm for Historical Economics." In D. Foray and C. Freeman, eds., *Technology and the Wealth of Nations.* London: Pinter Publishers.

David, P.A. 1997. "Path Dependence and the Quest for Historical Economics." University of Oxford: Discussion Papers in Economic and Social History No. 20.

Davids, K. 1993. "Technological Change and the Economic Expansion of the Dutch Republic, 1580-1680." *Economic and Social History in the Netherlands* IV: 79-104.

Davids, K. 1995. "Shifts of Technological Leadership in Early Modern Europe." In K. Davis, ed., *A Miracle Mirrored: The Dutch Republic in European Perspective.* Cambridge: Cambridge University Press, pp. 338-66.

Dawkins, R. 1976. *The Selfish Gene.* Oxford: Oxford University Press.

DeLong, B. and A. Schleifer. 1993. "Princes and Merchants: City Growth Before the Industrial Revolution." Cambridge: NBER, Working Paper.

Dennett, D.C. 1995. *Darwin's Dangerous Idea: Evolution and the Meanings of Life*. New York: Simon and Schuster.

Deyon, P. and P. Guignet. 1980. "The Royal Manufactures and Economic and Technological Progress in France before the Industrial Revolution." *Journal of European Economic History* 9(3): 611-32.

Duran-Reynals, M.L. 1946. *The Fever Bark Tree: The Pageant of Quinine*. New York: Doubleday.

Durlauf, S.N. 1997. "Reflections on How Economic Reasoning can Contribute to the Study of Science." Santa Fe Institute: Working Paper No. 97-05-043.

Elliott, E.D. 1985. "The Evolutionary Tradition in Jurisprudence." *Columbia Law Review* 85: 38-94.

Epstein, S.R. 1998. "Craft Guilds, Apprenticeship and Technological change in Premodern Europe." *Journal of Economic History* 58(3): 684-713.

Goldstone, J.A. 1987. "Geopolitics, Cultural Orthodoxy, and Innovation." *Sociological Theory* 5: 119-35.

Greif, A. 1989. "Reputation and Coalitions in Medieval Trade: Evidence on the Maghribi Traders." *Journal of Economic History* XLIX(4): 857-83.

Hall, A.R. 1967. "Early Modern Technology to 1600." In M. Kranzberg and C.W. Pursell, Jr , eds., *Technology in Western Civilization*, Vol. 1. New York: Oxford University Press, pp. 79-106.

t'Hart, M. 1993. "Freedom and Restriction: State and Economy in the Dutch Republic, 1570-1670." *Economic and Social History in the Netherlands* IV: 105-130.

Hicks, J.R. 1969. *A Theory of Economic History*. London: Oxford University Press.

Hohenberg, P. 1992. "Urban Manufactures in the Proto-Industrial Economy: Culture vs. Commerce." In M. Berg, ed., *Markets and Manufacture in Early Industrial Europe*. London: Routledge.

Hoock, J. and B. Lepetit. 1987. "Histoire et propagation du nouveau." In B. Lepetit and J. Hoock, eds., *La ville et l'innovation*. Paris: Editions de l'Ecole des hautes études en sciences sociales.

Hull, D.L. 1988. *Science as a Process*. Chicago: University of Chicago Press.

Jacobs, J. 1984. *Cities and the Wealth of Nations*. New York: Random House.

Jones, E.L. 1981. *The European Miracle*. Cambridge: Cambridge University Press.

Kauffman, S.A. 1995. *At Home in the Universe: The Search for the Laws of Self-Organization and Complexity*. New York: Oxford University Press.

Krusell, P. and J.-V. Rios-Rull. 1996. "Vested Interests in a Positive Theory of Stagnation and Growth." *Review of Economic Studies* 63: 301-29.

Kuznets, S. 1965. *Economic Growth and Structure.* New York: W.W. Norton.

Landes, D.S. 1993. "The Fable of the Dead Horse or the Industrial Revolution Revisited." In Joel Mokyr, ed., *The British Industrial Revolution: An Economic Perspective*. Boulder: Westview Press.

Loch, C.H. and B. Huberman. 1997. "A Punctuated-Equilibrium Model of Technology Diffusion." Mimeo.

Lopez, R.S. 1971. *The Commercial Revolution of the Middle Ages, 950-1350.* Englewood Cliffs: Prentice Hall.

Mayr, E. 1970. *Population, Species, and Evolution*. Cambridge, MA: The Belknap Press.

Mayr, E. 1991. *One Long Argument: Charles Darwin and the Genesis of Modern Evolutionary Thought.* Cambridge, MA: Harvard University Press.

Mokyr, J. 1990. *The Lever of Riches: Technological Creativity and Economic Progress*. New York: Oxford University Press.

Mokyr, J. 1991. "Evolutionary Biology, Technological Change, and Economic History." *Bulletin of Economic Research*. 4(2): 127-49.

Mokyr, J. 1992. "Is Economic Change Optimal?" *Australian Economic History Review* XXXII(1): 3-23.

Mokyr, J. 1994a. "Progress and Inertia in Technological Change." In J. James and M. Thomas, eds., *Capitalism in Context: Essays in honor of R.M. Hartwell.* Chicago: University of Chicago Press.

Mokyr, J. 1994b. "Cardwell's Law and the Political Economy of Technological Progress." *Research Policy* 23: 561-74.

Mokyr, J. 1995. "Urbanization, Technological Progress and Economic History." In H. Giersch, ed., *Urban Agglomeration and Economic Growth.* Berlin: Springer Verlag, pp. 3-37.

Mokyr, J. 1996. "Evolution and Technological Change: A New Metaphor for Economic History?" In R. Fox, ed., *Technological Change.* London: Harwood Publishers.

Mokyr, J. 1998a. "The Political Economy of Technological Change: Resistance and Innovation in Economic History." In M. Berg and K. Bruland, eds., *Technological Revolutions in Europe: Historical Perspectives*. Chelten, UK: Edward Elgar.

Mokyr, J. 1998b. "Induced Technical Innovation and Medical History: an Evolutionary Approach." *Journal of Evolutionary Economics* 8(2): 119-37.

Mokyr, J. 1999. "Innovation and Selection in Evolutionary Models of Technology: Some Definitional Issues." In J. Ziman, ed., *Technological Innovation as an Evolutionary Process*. Cambridge: Cambridge University Press, forthcoming.

Nelson, R.R. 1995. "Recent Evolutionary Theorizing About Economic Change." *Journal of Economic Literature* XXXIII: 48-90.

North, D.C. 1990. *Institutions, Institutional Change, and Economic Performance*. Cambridge: Cambridge University Press.

Olson, M. 1982. *The Rise and Decline of Nations.* New Haven, CT: Yale University Press.

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

Pirenne, H. 1937. *Economic and Social History of Medieval Europe*. New York: Harcourt Brace.

Prescott, E. 1997. "Needed: A Theory of Total Factor Productivity." Federal Reserve Bank of Minneapolis, Staff Report No. 242.

Price, D.J. 1957. "The Manufacture of Scientific Instrument from c. 1500 to c. 1700." In C. Singer et al., eds., *A History of Technology*. Vol. 3, *From the Renaissance to the Industrial Revolution, 1500-1750*. London: Oxford University Press.

Richards, R.J. 1987. *Darwin and the Emergence of Evolutionary Theories of Mind and Behavior*. Chicago: The University of Chicago Press.

Rosenberg, N. and L.E. Birdzell. 1986. *How the West Grew Rich: The Economic Transformation of the Industrial World.* New York: Basic Books.

Sale, K. 1995. *Rebels Against the Future: the Luddites and their War on the Industrial Revolution*. Reading, MA: Addison Wesley.

Smith, A. [1766] 1978. *Lectures on Jurisprudence.* Oxford: Oxford University Press.

Smith, A. [1776] 1976. *The Wealth of Nations*. Oxford: Oxford University Press.

Tenner, E. 1997. *Why Things Bite Back: Technology and the Revenge of Unintended Consequences*. New York: Alfred A. Knopf.

Van Uytven, R. 1971. “The Fulling Mill: Dynamic of the Revolution in Industrial Attitudes.” *Acta Historiae Neerlandica* 5: 1-14.

Vincenti, W. 1990. *What Engineers Know and How They Know It*. Baltimore: Johns Hopkins Press.

Unger, R. 1978. *Dutch Shipbuilding Before 1800.* Assen, The Netherlands: Van Gorcum.

de Vries, J. 1984. *European Urbanization, 1500-1800.* London: Methuen.

de Vries, J. and A. van der Woude. 1997. *The First Modern Economy: Success, Failure and Perseverance of the Dutch Economy, 1500-1815*. Cambridge: Cambridge University Press.

Wilson, T.C. 1985. “Urbanism and Tolerance: A Test of Some Hypotheses.” *American Sociological Review* 50: 117-23.

Witt, U. 1997. “Economics and Darwinism.” Max Planck Institute for Research into Economic Systems: Papers on Economics and Evolution No. 9705.