Invention and Rebellion:
Why do Innovations Occur at all? An evolutionary approach.

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Introduction

How are we to think of the *fundamental* causes of technological change? I should like to argue here -- but not demonstrate -- that standard neoclassical economic models perform poorly in explaining technological progress. In a recent paper, Edward Prescott (1997) has noted the failures of standard theory to explain the huge differences in incomes and productivity. Instead of criticizing standard analysis again, I propose to experiment with an alternative. In the paper below, I propose to 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 proposed first by

Donald Campbell 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. Below I will argue that the role of small groups 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.

Below, 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 argue why relatively small units might have an advantage here, and finally apply this model to re-tell the story of the economic importance of the City-state in technological history.

A few definitions.

To start off, we need a definition of what essential elements constitute a Darwinian model. It will surely come as no surprise that there is little consensus on the matter amongst biologists or evolutionary theorists on the matter. Darwinian models encompass a larger set than just the evolution of living beings whence it first originated. Darwin himself recognized the applicability of random variation with selective retention to changes in language. Douglass North (1990) has suggested a similar approach to the development of economic institutions, Richard Dawkins (1976) to the realm of ideas ("memes") and Daniel 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 such dynamic models. The main idea of a Darwinian model is a system of self-reproducing units (techniques) that changes over time. A Darwinian model consists in my view of three fundamental elements (Mokyr, 1998).

One is the notion of the relation between an *underlying structure* that constrains but does not whole 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, I submit, 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 Simon 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 Σ, contains but is not confined to consensus scientific knowledge. It also contains beliefs, traditions and other knowledge systems

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

[2] See Mokyr, 1991, 1996, and 1998.

which may not get down to the principles of *why* something works but all the same codify it and 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 such beliefs are held by *somebody* they must be included in Σ 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 8. 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 determine whether this particular technique will be actually used or not, in similar way to the fashion 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. 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 implies 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. In this kind of a model techniques "reproduce" from period to period and thus "carry" the knowledge embodied in them over time. A technique, in this view, uses human agents to reproduce itself to make another technique much like 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 t is dependent entirely on the state in $t-1$ and 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. If the agent changes, as 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 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 characteristics), evolutionary processes belong to a special group of Markov chains known as "branching processes." In these model 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, 1997). A multiplicity of conceivable outcomes with the actual result often determined by historical contingency is thus part and parcel of the process. Yet it is not quite 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 which carry them. In technical knowledge systems there are two stochastic process at work: the useful knowledge reproduces itself over time with possible "mutations" (discoveries about natural phenomena). The techniques also reproduce themselves and there, too, there can be change, say, through experience and learning by doing. The two stochastic processes are clearly related, with feedback going in both directions. Such feedbacks do *not* occur in living beings, where Lamarckian feedback mechanisms from phenotype to genotype are ruled out. This two-pronged stochastic process is depicted in fig. 1.

Third, there is a property of superfecundity in the system, that is, there are more entities that can be accommodated, so that there must 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, however, selection is not a metaphor for an invisible hand kind

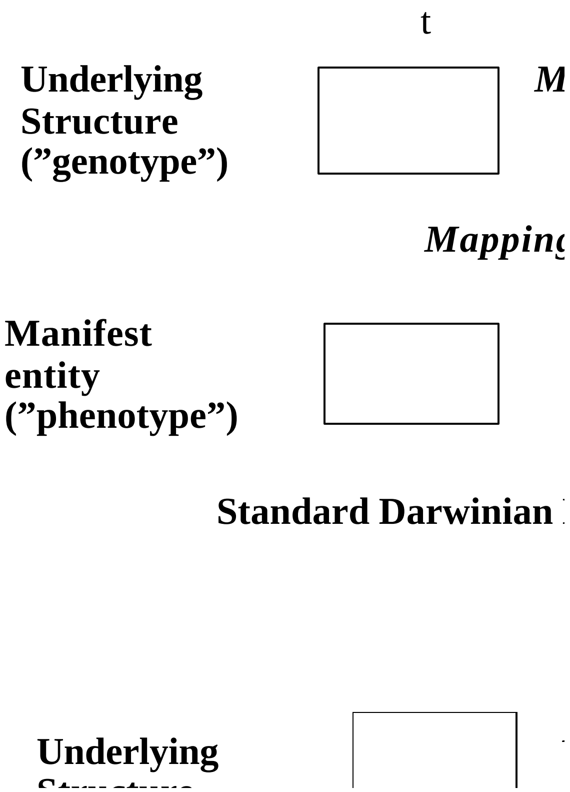

Figure 1

of mechanism that operates in a decentralized and unconscious manner: there are actually conscious units, firms and households, that do the selecting.[3] It is less clear what exactly is meant by selection at the level of the underlying structure. 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. One has to specify some form of congestion caused by storage cost, some constraint that requires society to shed some pieces of knowledge as it acquires and selects better ones. Whereas this is surely true for an individual

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[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.

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. While of course there is incommensurability between certain views of nature so that some theories are rejected, they are not necessarily *extinct* in the technical sense of being inaccessible. Thus the humoral theory of disease is still understood today, but no longer serves as a source for prescriptive techniques in modern medicine. Scientific theories that are “accepted” will normally be the ones that are mapped onto the techniques in use, whereas the ones that are rejected will be dormant, known only to historians of knowledge or stored in library books. Accepting the work of Lavoisier meant that one had to abandon phlogiston theory but not destroy any trace of it. Copernican and Ptolemaic views of the Universe reside together in Σ, though of course not in the same position.

Insofar that there is incommensurability between different subsets of Σ, people have to choose again (Durlauf, 1997). We need to distinguish between knowledge that is “widely accepted” (consensus) and widely believed to be false. Absolutes are of course 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 ones that map this knowledge into techniques. When the selection environment on 8 is not too stringent, such techniques with different bases in Σ 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 Σ must also be divided into “active” and “dormant” knowledge, which are mapped or not onto 8, a bit like “coding” and “non-coding” DNA. Again, a grey area makes such distinctions somewhat tricky. Advances in paleontology or 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 Σ can become active given a change in the environment.[4] This is, I submit, what we must mean when we speak of induced technological change (Mokyr, 1998c). We can thus subdivide Σ 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 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. I see three different types of selection here. One is the standard neoclassical mechanisms: techniques are selected according to whether they maximize some kind of objective function. This includes supply considerations (which techniques work at all and do so more efficiently than others), 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. There are however two other kinds of mechanisms that are of major historical importance here. One is what may be called hysteresis or inertia. In any Markov chain we can build in as much inertia as we want. We can also build in irreversibilities of any degree. In

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[4] By “environment” here I mean not only the physical environment in which the technique operates but also the development of complementary or rival techniques which may lead to the activation of previously dormant knowledge. Indeed, such processes are what constitutes “adaptation” in all evolutionary processes.

biological evolution a camel cannot change into a zebra once it discovers that zebras are more suitable to a given environment. In technological evolution such changes can and do occur, but they do so at a cost, often quite high. Secondly, selection occurs at a social level, much like the social constructivists tell us. 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 model could of course be incorporated into the objective functions and reduced to "what does the market want" but it seems instructive to distinguish between criteria that relate to the actual functioning of a technique and other characteristics.

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, Alfred Marshall and the neo-Darwinian phylogenetic gradualist orthodoxy in evolutionary biology hold, or can it move in bounds and leaps as Eldredge and Gould 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 this. Are Darwinian models of natural selection sufficient to explain the course of history as the ultra-Darwinians such as Dennett and Dawkins claim, or do we need additional inputs from chaos theory, self-organization theory, or something yet unsuspected? Clearly these debates mirror those between the scholars who insist on multiple equilibria and hence path-dependence such as Brian Arthur (1994) and Paul David (1992, 1997), and their opponents such as Liebowitz and Margolis (1995) who feel that the rational market -- if only left alone -- will get it right every time. What exactly is the relation between the environment and technological selection, and can we distinguish meaningfully between adaptation and innovation? Are traits invariably explicable in terms of their functions, as the fundamentalist adaptationists claim? 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 a-historical? Here, as promised, I shall take a look at why innovation occurs at all, and whether that should surprise us.

Change and Inertia in evolutionary systems.

I would like to suggest first to develop a few simple tools and then use them to distinguish between technological adaptation, technological mutation, and technological recombination technological speciation. These terms are of course borrowed from biology, but they will mean somewhat different things, and throughout this discussion we need to keep reminding ourselves that the fields are really intrinsically different in many dimensions.

First, consider the selection mechanism on techniques. Suppose that a technique has only two "traits" that define it. Call these T_1 and T_2. We can think of those, say as "output quality" and "costs of production" although many different kinds of attributes may matter here. Secondly, each time a technique is "used" it "lives" and a specimen has been "selected." The environment, V, is defined as anything external to technique j that is not part of it, including but not confined to the T's of other techniques. For each technique, we may then define μ(j), which is a count of how many times technique j is used, a bit like the size of a population. For any set of traits and an environment, we can define an equilibrium level of μ^*

(1)
mu ^ * (j) ~ \=\ ~S(T sub 1 sup j, T sub 2 sup j ... T sub n sup j; V)

and μ

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= f(μ^* - μ). For any V, there are combinations of the T's which define μ

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= 0. Assume for simplicity that $M\mu/MT_1 > 0$ (the trait is favorable) and that $M^2\mu/MT_1^2 < 0$ (diminishing returns) and the same holds for T_2. We can then define the curve ZZ' in fig. 1 which defines the condition of fixed fitness (μ

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= 0). A deterioration in the environment (possibly due to changes in complementary or rival techniques, or a change in preferences) would be depicted as an outward shift of ZZ'. Each technique in use is defined as a point in this space. In addition to the techniques actually in use, given by the area ∗ in fig. 1, there is a larger set of all feasible techniques 8 within which ∗ is wholly contained. The relationship between 8 and total human knowledge is precisely the relationship between the underlying structure or "genotype" and the manifest entity or "phenotype" but of all the possible entities only a small subset get selected.

Technological selection thus occurs at two levels: not all techniques in 8 are picked to be in ∗. In fact only a small minority of all feasible and known ways of making a pencil, shipping a package from Chicago to New York, or treating a patient suffering from Pneumonia are in actual use at any point of time. Secondly, techniques in use themselves are competing over the scarce resource of a finite number of usage, and in the long run, assuming competition is sufficiently stringent, only the ones that are at E_0 actually maintain their numbers.

Beyond the level of the selection of techniques there is a higher level of selection at the level of knowledge Σ. As I noted above, superfecundity is strictu sensu not applicable here. In practice, however, new knowledge normally replaces existing knowledge that becomes obsolete and thus inactive. The vast bulk of Σ is dormant either because there is no known way in which this knowledge can be used to map into anything useful (say, the speed at which the planet Uranus circles around the sun) or because the knowledge is out of favor and believed to be inaccurate. The latter requires selection which in the realm of knowledge requires standards of evidence, proof, and persuasion.The Σ set thus contains a huge amount of knowledge that is not actually active that is, it is not mapped onto the set of useful techniques 8 much like genes that

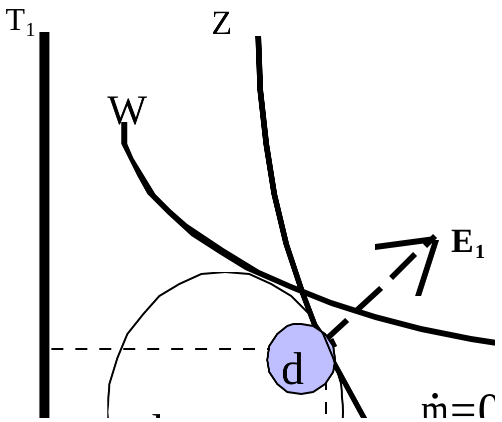

Figure 2

are not expressed. What is unique about any evolutionary theory of useful knowledge is that there is feedback from 8 to Σ, as fig. 1 demonstrates:

parts of Σ were selected (that is, chosen over incommensurable parts) *because* they mapped into techniques that were superior by some obvious criterion. Such advances in usages in some cases led to significant expansions in Σ, of which the steam engine and the subsequent advances in thermodynamics, and the serendipitous discovery of aniline purple, leading to the advance in organic chemistry in the 1860s.

In many cases new and potentially useful knowledge emerged but failed to be expressed, that is, failed to persuade enough people to end up being translated into the accepted subset of Σ and thus to be mapped into 8. Thus the germ theory of disease was first proposed by Girolamo Fracastoro in the sixteenth century and proposed repeatedly without having influence on the practice of medicine until late in the nineteenth century. Conversely, much of the knowledge set in the past may be recognized today as "false" and yet has historically mapped into useful techniques. One can navigate a ship using the stars even using a Ptolemaic geocentric astronomy and improve the techniques of iron production on the basis of phlogiston chemistry. Medical procedures based on Galenian medical theory could at times be effective. Selection, in short, occurs at both ends of the mapping function but whereas selection in 8 is at least in some cases performance-tested, selection in Σ requires tools of persuasion, some rigorous, some purely rhetorical.

A glance at figure 2 demonstrates how evolutionary concepts can be invoked to understand technical change as a historical process. The set 8 contains all feasible techniques in a given society, and illustrates how *adaptation* occurs as a consequence of changes in the environment: if the frontier ZZ' shifts around (say, to WW') and its tangency moves elsewhere, society can pick another technique somewhere in 8 and thus adapt to the changed environment. It can also go back and search over Σ to see if there is a way of endogenously expanding 8. There is no guarantee than such searches lead to results; indeed, normally they do not.[5] For evolution to

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[5] Steven Pinker (1997, p. 206) cites Lamarck as saying "new needs which establish a necessity for some part really bring about the existence of that part as a result of efforts" and adds, "if only it were so -- if wishes were horses, beggars would ride."

work, it has to find the answer to changing needs within the *existing* raw material. The differences between a search over 8 and one over Σ is roughly equivalent to phenotypical and genotypical adaptation in living beings, always remembering that in living beings the "search" is purely metaphorical, the result of an invisible hand working through differential survival and reproduction, whereas in knowledge systems the "survival" and "differential reproduction" of bits and pieces of knowledge is often the result of willful and intentional actions of agents. In knowledge systems, but *not* in living beings, it is conceivable for Σ to respond to some extent to changing needs. For example, pure research might be partially motivated by possible applications. Most major historical scientific breakthroughs were clearly not of that nature, but it is possible (especially in modern time) that some expansion in the knowledge base, for instance in molecular biology or materials science, are motivated in part by some applications.

What needs to be emphasized here is that in all evolutionary systems, and technological systems included, there is 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 (that is, additions to 8) are likely to be an extension and modification of existing techniques. Localized learning is more common than technical changes in a completely novel region (David, 1975), so that we can expect changes in 8 to take normally the form of pimples and protuberances appearing on the frontier of 8. 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 macroinventions 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 purely based on reproductive isolation which is not a binary variable. In any event biological distinctions are rather more arbitrary in higher genera. Yet in most dynamic systems satisfying the criteria I outlined 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, yet closer to it than to a toothbrush.

My point is that macroinventions 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 microinventions which I first proposed in 1990 has been 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 that lend themselves to that.

One useful way to think about the economic history of technological progress is to think of it in terms of evolutionary trajectories that begin through a sudden novelty or macroinvention, which then are continuously improved and refined through a multitude of microinventions. Those refinements eventually run into diminishing returns and asymptote off, at which point stasis is likely to occur until “punctuated” by a new macroinvention. It could be said that microinventions occur within an existing technological paradigm and are part of “normal technological change” whereas macroinventions 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 we can tell can necessarily be reduced to this simple dynamic story. There are times, for instance, that the macroinvention 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. That raises the stakes in understanding where macroinventions come from. Rather than attacking this question head-on, I propose to examine a somewhat more manageable one: 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 this is more likely to occur in comparatively small and relatively closed communities such as urban areas?

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 observe periods of very rapid change known sometimes as “adaptive radiation.” It might be tempting to think of exogenous agents, such as “mutagens” that somehow affect the rate at which novelty occurs. In biology, such 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 such “mutagens.” While concepts such as mutation and recombination can perhaps be identified, the process is quite different. One property shared by all evolutionary systems, however, is that their rate of change depends not so much and their ability to generate innovations as such but for those innovations to be selected and become part of the set of manifested entities.

This is particularly true when it comes to the creation of new entire groups (or classes) 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 Ernst Mayr’s (1970) concept of *geographic (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 counterpart in cultural and informational evolution because concepts of homozygosity and heterozygosity (and hence recessive and dominant genes) have no equivalent outside of biology. At that level of abstraction, arguing from 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 Stuart Kauffman (1995) has called the hypercritical region. In biology the resistance shows up first in the absence (or extreme rarity) of anything that resembles a Lamarckian mechanism. A genotype is set upon meiosis. If Lamarckian change could occur, the rate of change of an evolutionary system would accelerate and stability would be unthinkable.[6] Even with the Weissmanian constraints, change is very rare, with resistance to change built in at any stage. As Mayr (1991, pp. 160-161) has explained, "Just exactly what controls this cohesion is still largely unknown, but its existence is abundantly documented...during the pre-Cambrian period, when the cohesion of eukaryote genotype was still very loose, seventy or more morphological types (phyla) formed. Throughout evolution there has been a tendency for a progressive "congealing" of the genotype so that deviation from a long-established morphological type has become more and more difficult." While such genetic cohesion has of course not precluded the well-known adaptive radiations which created different species, these explosions of variety are little more than ad hoc variations on a *bauplan* or structural type. 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, p. 73).

Such resistance also exists in knowledge systems and therefore in technology. They are a direct consequence of superfecundity in the set 8: a lot of new ways to carry out a particular production are "proposed" or "occur to individuals" but unless the vast majority of such suggestions are rejected, the cost of continuous experimentation and change would become infinite and the system would turn into complete chaos. Even for unequivocally superior techniques, however, resistance is likely because given the finiteness of the number of techniques in use, they are likely to replace existing techniques. In knowledge systems, existing techniques are embodied in agents using them, and these agents operate as intentional and rational agents. One can think therefore readily 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 Σ 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 such as 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.[7] 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. Yet new words and usages, forms of spelling and even grammatical rules do eventually make it through or languages would remain immutable over long periods. It is just that only the tiniest fraction of them ever have a chance, and of those another very tiny fraction gets selected. My point, then, is that innovations can be explained either by the frequency of them occurring at all or by the receptivity of their environment to them. In what follows below I will discuss the

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

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

latter in an attempt to assess the historical sources of resistance to technological innovation. In the history of technology we can distinguish a number of different sources of resistance. None of these have exact counterparts in evolutionary biology nor should we expect there to be any; what matters is that there is resistance to change.

1. *Economically motivated resistance*: groups in the economy may resist change because changes in technology may benefit other groups at their expense. Workers in danger of losing their jobs, facing changes in their work environment, or fearing that their human capital will depreciate are one example of this, but many others can be imagined as well.
2. *Ideologically motivated resistance*: these include various sources of political resistance that are not fueled by direct economic motivation: technophobia, neophobia, a sense that meddling too much with the creation and nature is in some way sinful, or a high degree of risk aversion with particular high cost 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 way such resistance takes, then, is as an ideology of *conformism* in which deviancy -- whether technological, political, religious or ethnic -- is actively discouraged.[8]
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 till 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 those of others only through the price mechanism. In other words, a change in a particular technique will

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[8] Yet conformism also means that new knowledge will be resisted unless it fits into an accepted paradigm. In other words, the mappings from Σ into 8 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 Σ. Thus when quinine was first introduced into Europe, it was resisted for a number of reasons, at least one of them being that it did not mesh with accepted Galenian practice. On the other hand, 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). Yet 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 Σ are still regarded with great scepticism even if they are widely used. The same is true by the polygraph machine which relies on a questionable foundation in natural knowledge and whose actual effectiveness, much like homeopathic medicine is controversial (Alder, 1998).

drive up demand for complements and reduce that for substitutes. As long as there are no strong network externalities, it may not matter what happens to other techniques. But such externalities have always existed, even if their extent may have been limited.[9] 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 has to take this into consideration. Technological change in a "system" becomes a coordination game which may have multiple stable solutions. Once settled on a solution, it may require a substantial cost advantage for the system to move to a different one (Loch and Huberman, 1997). In our own age, network externalities (broadly defined) place serious limits on the degree and direction technology can change at any given time. 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-capable," electrical tools require 115 V, car engines are constrained to gasoline and diesel fuels. Such standardization problems can be overcome, but only at a high cost, so that they impose an effective constraint on new techniques, and constitute a source of resistance. Such failures often lead to government intervention.[10]

5. *Frequency dependence*. In many cases, the rate of technological change and the rate of adoption depends 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 down 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; obviously, the more people that have read a book, the more likely it is for that book to be read by even more people. Some books become winners 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 is an example of systems with positive feedback (Arthur, 1994). In any case, frequency dependence means that it is often difficult to break into a

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

[10] 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* "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." *The Economist*, May 2, 1997, p. 18.

> market with a new product, for instance if there is no name recognition or there are no service networks. Frequency dependence can mean 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 of a new technique or product, that is, 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 -- 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 which have been so truly overwhelming in their superiority that no effective resistance could be put up. The mechanical clock and moveable type, a quarter of a millennium apart, simply swept Europe off its feet. Both of them were "macroinventions" by the standards described above. Among the nineteenth century inventions, the telegraph and x-ray photography were of that nature. These advances share the feature that the improvement 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 is quite different). Is such resistance normally more easily overcome in compact or large, open or closed communities?

The concept of a community here is not identical to the political unit, and I do not wish to argue that for that reason small countries have an edge over larger ones. Communities can be subsets of national units or transcend them. 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 idea, 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 argue 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. It is important to stress that 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, on the other hand, normally are distributed over a large population of consumers, 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 affected producers organizing.

Perhaps more relevant is the simple fact is that small economies tended, all other things equal, to be more open to the rest of the world that larger units. 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 obviously 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, open-ness. The effect, however, is quite similar.

The *ideological element in the social resistance* to innovation works quite differently. To be sure, here, too open-ness to the rest of the world will make 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 always 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.

Third, 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 in which the inventor operates the larger 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 open-ness, by itself this element seems to argue against 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 normally there are economies of scale in information networks, it is possible to imagine a small enough 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 argue below, relatively compact, dense units such as cities may have been optimally sized for technological advances.

Network externalities, on the other hand, are strongly correlated with size. Indeed, some network technologies tend to help *create* larger communities (think of 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.

Yet there are at least two complications here that make the connection more complex and ambiguous. First, it is unclear whether what counts is total or per capita costs. Secondly, 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), those costs would be higher in small communities, and this would imply that existing techniques are more deeply entrenched and more difficult to displace in large communities.

The City State: an Assessment[11]

In modern economies, it is sometimes thought that technological change is a conscious and deliberate function of the resources devoted to Research and Development. Such a view is not wholly without its critics, but it surely is less true for technological progress -- 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 relation between the social environment and its ability to overcome the built-in resistance to change, and technological performance. What I propose below is to 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, and administrative-ecclesiastical centers. Many cities, of course, served some combination of all three of these functions. It may seem 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 little or no dependency on a larger state. By way of contrast, those metropolitans 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, say, Florence with Paris or Hamburg with Vienna, is not just in function but in their political status. This distinction, too, suffers from the pitfalls of a dividing line along a continuous variable. Famous city states like Carthage, Amsterdam, and Venice controlled in their zenith (or after it) fairly substantial territories, while the amount of territory controlled from, say, 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

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[11] The following is adapted with substantial revisions from Mokyr (1995).

traders engaged in external trade”. Rosenberg and Birdzell (1986) followed him in this emphasis. 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 (gains from trade) supported by unique institutions defending property rights.[12]

How much evidence in European history is there to support a correlation between the special process of urbanization that produced city states and technological development? Scholars, writing mostly about the modern period, have had few doubts.[13] 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.[14] Italian city states in the early Middle Ages, on the other hand, began their growth as a consequence of technological progress as much as of 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.[15] Other Italian towns led the world in innovations in fine textiles, in metalworking, in the use of chemicals, and later in printing, clockmaking, optics, cartography, and instrument and gunmaking. One historian, after describing the technical advances of the

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[12] The idea that the citizens of city states enjoyed better and more secure property rights is an old one that has recently been revived by DeLong and Schleifer (1993) who argue that the freedom from arbitrary taxation in non-despotic governments was conducive to economic growth (and thus, 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 clearly 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 that “one cannot assume that incremental urbanization *necessarily* denotes incremental economic growth” (1984, p. 246).

[13] Ester 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." Paul Bairoch, writing about a more modern period, asks rhetorically whether the city has not had a considerable hand in stimulating invention and ensuring its diffusion (Bairoch, 1991, p. 160) 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). Jane Jacobs (1984, pp. 224-225) 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).

[14] Baghdad, for instance, was an important center preserving Hellenistic technology and funnelling 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). Yet Islamic technology, whether it lacked originality or not, ran out of steam rather quickly and was eventually outdone by the ingenuity of Western Europeans.

[15] 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.

Italian Renaissance, concludes that "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 such as 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.[16] 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 ship-building 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 windpower 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 clockmaking to medicine (De Vries and Van Der Woude, 1997, ch. 8). Within the Dutch cities, technological specializations occurred, underlining the importance of a division of labor and external economies. 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 was Denis Papin, 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 credited with the invention of the microscope, built a prototypical submarine, and made many important improvements to furnace making, metallurgy, clockmaking, and chemicals.

It is easy to think of reasons why technology in this period developed faster in cities than in the countryside. For one thing, 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. Yet such a link by itself 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 such a link

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[16] 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.)

questionable.[17] 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 (Weitzman, 1995). 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 the model into successful products. High levels of skill tended to exist largely in urban areas because of the finer division of labor there. 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.[18] Towns contained literate people, and eventually became the sites for institutes of higher learning, libraries, and the residence of scientists. Cities have been argued 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).[19] Cities have also been

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[17] Both imperial Rome and Manchu (Qing) China are examples of systems dependent on Smithian growth in which technological achievements were modest by comparison. On the other hand, 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.

[18] David Landes (1993, p. 159n) points to the special skills of clock- and instrument makers as evidence of Smith's view Some of those clock and instrument makers, to be sure, 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 ([1776], 1976, pp. 781-82) pointed that out 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 ([1766], 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).

[19] Tolerance and pluralism have been widely regarded in the literature to be important elements in the environment fostering technological progress. Bairoch 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.

argued to direct stimulate agricultural improvement. E.A. Wrigley (1987, p. 190) has argued that "the extraordinary stimulus afforded by the growth of London... was probably the most important single factor in engendering agricultural improvement."[20] It is telling that convertible husbandry, one of the most important productivity-enhancing innovations in European agriculture originated in the late middle ages in the urbanized lands of Flanders.

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[20] The difficulty with the argument is that it does not adequately distinguish between growth that occurs because of gains from regional specialization or other commercial factors, and technological progress strictu sensu. Similarly, it has recently been maintained by Hoffman (1996) that in seventeenth and eighteenth century France there is evidence that cities were a cause of a growth in agricultural productivity in the surrounding countryside. Yet he is unsure what the exact economic mechanism was that led to this phenomenon. As he admits (p. 174), it seems unlikely that -- at least in early modern Europe -- cities facilitated the spread of new agricultural techniques. The observed increase could be the side effect of some trade-related effect, such as the shipping of urban fertilizer to the nearby countryside or the shift of farmers near cities into high-value garden crops.

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 cartellization. Some inventions required a critical mass of nearby customers and thus areas of high density: the medieval mechanical clock, first constructed as part of urban churches, is an example.[21] Finally, we too often think of technological diffusion as mere information flows. It is often overlooked, however, how much simple *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, doing so on some minimal scale), 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 such 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.[22]

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 of course 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 matters 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 most 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.[23] Moreover, luxury demand by rich and lavish courts rarely spawned much innovation and had a large import component. By

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[21] Hoock and Lepetit (1987, p. 22) draw an analogy between the medieval public clock and late nineteenth century telephones. Yet the telephone, as it soon was extended to rural regions, serves also as a reminder that technological changes could easily negate the advantages in communication enjoyed by the inhabitants of urban areas. Cf. Hoock, Jochen and Lepetit, Bernard, 1987. 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.

[22] Bairoch 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 simply because each individual meets on average a great deal more people. Cf. Paul Bairoch, 1991, p. 169.

[23] 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.

and large Imperial cities diverted resources and talents into non-technological channels such as administration, the military, and religion. At times, such efforts 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, then, 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 have tended to move 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. To be sure, some urban economies such as sixteenth century Antwerp were devastated militarily before they reached that stage, but those that, like Venice and Amsterdam were able to survive 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 previous work I have termed this historical regularity "Cardwell's Law" (Mokyr, 1990, 1994b).

What accounts for Cardwell's Law? One reason for Cardwell's law is well explained by the framework set up by Mancur Olson (1982), who argues 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. Yet it is inevitable perhaps that sooner or later the existing physical and human capital of the members will become an object of political protection, and that means that almost all innovation 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 they can, will 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 tried one, implying that when a macroinvention radically changes production technology, it is likely to take place in a new site rather than take on 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 to the point where many urban economies eventually entered periods of technological stasis. The traditional literature seems unambiguous about this phenomenon. Kellenbenz (1974, p. 243), for example, simply states that "guilds defended the interests of their members against outsiders, and these included the inventors who, with their new equipment and techniques, threatened to disturb their members' economic status. They were just against progress." Much earlier Pirenne (1936, pp. 185-86) pointed out that "the essential aim [of the craft guild] was to protect the artisan, not only from external competition, but also from the competition of his fellow-members." The consequence was "the destruction of all initiative. No one was permitted to harm others by methods which enabled him to produce more quickly and more cheaply than they. Technical progress took on the appearance of disloyalty".[24] There are many other examples of guild

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[24] For a description of Italian guilds, see Cipolla (1968).

resistance to change, analogous to the kind of resistance that occurs in other evolutionary systems.[25]

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. Yet their impact on technology should not be regarded as pervasive, much 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 around rural sources of energy, minerals, and cheap labor, often geographically inevitable but also at times production moved to the countryside just 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 forced some technologically dynamic industries to be located in the countryside no matter what. But some of inventions could be worked just as well in the countryside as in cities: the new spinning wheels and horizontal looms, which appear in the eleventh and twelfth centuries, were operated in worker's homes, whether in the cities or in the countryside. For centuries, the textile industries of the Flemish and Toscan towns competed with their respective countrysides. 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, S.R. Epstein (1997) has argued 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 and may have helped to avoid the dangers of underinvestment in human capital that are part of any training system in which general skills are being taught at a cost to the instructor. Yet 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. Whether the system ever quite reached the limiting case of complete stasis or not, clearly 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 allow reasonable doubt among some economic historians as to their long run effect on technological progress.[26]

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[25] For the wool industry in medieval England see Carus-Wilson, [1941], 1966; 1952. 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; Audin, 1979.

[26] Hohenberg (1992, p. 167) feels that the picture of guilds resisting competitive forces and change “cannot be even remotely accurate”. Though he is correct in arguing 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 surely the case in *ancien régime* France. See for instance

Over time, however, the body of technical knowledge taught by urban masters to their apprentices became increasingly rigid and codified. Wherever they could, the urban guilds tried to make existing technology binding (usually with the objective or excuse of protecting quality reputation) and thus made it increasingly difficult for new ideas to be accepted.[27] In most of Europe, craft guilds gradually brought about a level of regulation that stifled competition and innovation. They laid down meticulous rules about three elements of production that we might term “the three p's”: prices, procedures, and participation. As guilds gained in political power, they tended increasingly to freeze technology in its tracks. The regulation of *prices* was inimical to technological progress because process innovation by definition reduces costs, and the way through which the inventor makes his profits is by underselling his competitors. Cartels regulating prices may still allow some technological progress because innovators can realize increased profits through lowering costs. To prevent this, *procedures* stipulated precisely how a product was supposed to be made and such technical codes would of course ossify production methods altogether. Enforcing these procedures, however, was far more difficult than enforcing pre-set prices. Finally, and in the long run perhaps the most effective brake on innovation, was *participation*: by limiting and controlling the number of entrants into crafts, and by forcing them to spend many years of apprenticeship and journeymanship, guild members infused them with the conventions of the technological status quo. Guilds stopped the fruitful exchange of information between different bodies of knowledge by enforcing a high degree of compartmentalization and specialization thus encumbering the flow of fresh ideas and the cross-fertilization between branches of knowledge that so often is the taproot of technological change. In Coventry in 1435 a prohibition was imposed on bringing together a number of different processes of metalworking under the same roof (Bolton, 1980, p. 266). In the 1560s, three Parisian coppersmiths invented improved *morions* (military helmets), but were prevented from producing them because the armorers held the exclusive rights to defensive weapons. In this case they were overruled by King Charles IX (Heller, 1996, pp. 95-96).

There is, then, an influential literature that places guilds and similar organizations at the center of stage in explaining the temporary nature of technological “adaptive radiation” in urban

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Deyon and Guignet, (1980). Clearly, however, Hohenberg's argument that guilds were a tool controlled by urban elites to impose stability on the cities is consistent with the argument made here.

[27] Exclusion of innovators by guilds did not end with the middle ages or even the Industrial Revolution. In 1855, the Viennese guild of cabinetmakers filed a suit against Michael Thonet, who invented a revolutionary process for making bentwood furniture. The *Tischlermeister* filed a lawsuit against Thonet claiming that he was not a registered cabinetmaker, which had to be overruled by making his workshop an “Imperial privileged factory.” See Ekaterini Kyriazidou and Martin Pesendorfer, “Viennese Chairs,” unpublished manuscript, University of Chicago and Yale University, June 1996.

areas. In the closing decades of the eighteenth century, Dutch reformers blamed the guilds as a source of their growing technological backwardness (Davids, 1995). Summarizing the rigidities in North Italian cities, Domenico Sella noted that "the very precocity [of the cities of Lombardy] had tended in the long run to breed complacency and an excessive reliance on traditional techniques and designs. The cities were thus clearly ill-suited to serve as the cradle of large-scale industrialization; far from being the vanguard of the modern economy, they must be viewed as anachronistic relics of a rapidly fading past" (Sella, 1979, p. 136).

Of course, in principle such institutions could emerge in the countryside as well. Unlike today, however, the problems in organizing Olson's “distributional coalitions” in rural areas turned out to be more severe. 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, and enforcement was cheaper in small and densely populated areas. If and when guilds were progressive agents, the cities' progressive elements benefitted; 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, it seems, 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. Hence the crystallization was rarely complete. Davids (1995) and Epstein (1997) 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.[28] The European city state was part of what E.L. Jones (1981) has termed the “states system” which provided European society with enough of a dose of inter-society competition to facilitate the long-term economic growth experienced by the Continent.[29] All the same, the states system worked primarily for Europe *as a whole*; what happened 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” which 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 plunderings. The prosperous and creative towns of

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[28] The Dutch Republic, a confederacy of semi-autonomous city states, was fortunately situated 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. 117-18).

[29] 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).

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, then, 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, it is clear that 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 contributed only for a limited period.

Conclusions

An evolutionary perspective, which focuses on the resistance faced by an innovation in a generally conservative environment, predicts therefore two testable hypotheses. One is that all other things equal, compact city states are more likely to be the loci of technological progress than rural areas or large Imperial towns. The other is that such advantages tend not to persist, and that whatever technological creativity occurs in such city states is of relatively short duration. History, of course, is not kind enough to let us test these hypotheses with the kind of rigor that scientific standards impose. Some technologies lent themselves naturally to either urban or rural regions. Furthermore, military and political events may be in part to blame for the short life-span of urban centers of innovation. All the same the experience of urban Europe from the eleventh century on seems roughly consistent with these notions. This is far short of a rigorous test, but it suggests that evolutionary frameworks may be useful in re-thinking old issues in the creation and diffusion of new technological knowledge in historical contexts.

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