King Kong and Cold Fusion:
Counterfactual analysis and the History of Technology

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ABSTRACT

How “contingent” is technological history? Relying on models from evolutionary epistemology, I argue for an analogy with Darwinian Biology and thus a much greater degree of contingency than is normally supposed. There are three levels of contingency in technological development. The crucial driving force behind technology is what I call S-knowledge, that is, an understanding of the exploitable regularities of nature (which includes “science” as a subset). The development of techniques depend on the existence of *epistemic bases* in S. The “inevitability” of technology thus depends crucially on whether we condition it on the existence of the appropriate S-knowledge. Secondly, even if this knowledge emerges, there is nothing automatic about it being transformed into a *technique* that is, a set of instructions that transforms knowledge into production. Third, even if the techniques are proposed, there is selection which reflects the preferences and biases of an economy and injects another level of indeterminacy and contingency into the technological history of nations.

Introduction

What do we mean by "historical contingency"? It means at the most intuitive level that the things that really happened in history did not have to happen, that something else *could* have happened. Counterfactual analysis then looks at that "something else" and wonders what it could be and what antecedent would have to be true for it to happen. For an economist, contingency can be formulated in terms of the uniqueness and stability of steady states or historical trajectories. The issue of contingency revolves around how many dynamic equilibria there are. In the limiting case there is a unique and stable path, to which the economy always returns even if accidents cause temporary derailments. But if the system has more than one such steady state, as is likely, small events and shocks might determine whether the system ends up in one or another. If the system is at an unstable equilibrium, a minor perturbation might throw it off course and it may never return to its original path. For a historian, the issue seems altogether more obvious: of course different outcomes must have been possible since so many times accident and serendipity can be shown to be of importance. How *much* different the outcome would have been had some initial conditions differed, is of course more controversial, as the essays in this volume attest.

How "contingent", then, is *economic* history? In much of the literature, there is little doubt that it is the least contingent kind of history. Marx's inexorable forces of historical materialism literally left little to chance. Few opportunities were left to luck, accident or even individual action in a world governed *au fond* by class struggle and the forces of production. In an 1894 letter, the aging Engels wrote that

> "Men make history themselves, but not as yet with a collective will according to a collective plan... their aspirations clash and for that very reason all such societies are governed by *necessity*, the complement and form of appearance of which is *accident.* The necessity which here asserts itself athwart all accident is again ultimately economic necessity."[1]

On the right, mutatis mutandis, the same kind of arguments can be heard. The powerful, impersonal

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[1] Cited in Robert Tucker, (ed). *The Marx-Engels Reader*, 2nd ed., New York: W.W. Norton. 1978, p. 767

forces of free, competitive, and efficient markets mean that if a single individual, no matter how influential and successful, were missing, he or she would have been replaced by the spontaneous action of large social and economic factors.[2] Even a middle of the road, level-headed economic historian such as David Landes insists that major events in economic history must have deep causes, rooted in the foundational structure of a society. In other words, major trends in economic history are not contingent.[3]

At some basic level this statement must be incorrect. After all, economic history is affected by political history. If the first World War was a highly contingent event as argued convincingly by Ned Lebow, then many of the critical developments in the economic history of Europe may have been equally accidental.[4] The war was followed by two decades that were heavily flavored by the after-effects of the War. The European economies that had been cruising at a steady rate toward more integration and technological sophistication and had enjoyed rising incomes and living standards, were blown off course in a matter of days and took three decades -- and in Eastern Europe arguably far longer -- to resume their paths. For decades, the economic history of the continent was dominated by financial instability, fiscal chaos, inflation, unemployment, and balance of payments difficulties – none of which had been anticipated, let alone experienced at a remotely comparable scale before the fateful shots fired by Gavrilo Princip.[5] Nature can inject economic history with an element of chance as well: equally "contingent" was the accidental transport of a few spores of *phytophtora infectans* in a ship from the United States to Flanders in 1845 and from there by an unknown

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[2] Robert Paul Thomas, "The Automobile Industry and its Tycoons," *Explorations in Entrepreneurial History* Vol. 6, No. 2 (Winter 1969.), pp 139-57.

[3] David. S. Landes "What Room for Accident in History? Explaining Big Changes by Small Events." *Economic History Review* 47 (1994): 637-56.

[4] Richard Ned LeBow, "Franz Ferdinand found alive: World War I Unnecessary". In Richard Ned Lebow, Geoffrey Parker, and Philip Tetlock, eds., *Unmaking the West: Counterfactual Thought Experiments in History*, forthcoming.

[5] It might be recalled that Norman Angell wrote his *Great Illusion* (1910) arguing that War was illogical and unlikely since despite rising protection the European nations had become too closely integrated to wage war on each other.

route to Ireland. The resulting potato blight dramatically changed the course of Irish economic history and its lingering effects were still evident in 1950. It also had long-run effects on the demographic make-up of both the United Kingdom and the United States, to say nothing of a century of Anglo-Irish relations and British politics.

It is more difficult to make a strong argument for contingency and accident in the development of *technology*. Technological factors were an important element in economic growth in the West; in fact, the Industrial Revolution was the period in which technology elevated itself from a relatively minor contributor to growth to an important -- though never the *sole* -- factor behind the economic miracle we refer to as "the Rise of the West." Any story that concerns the inevitability of the Rise of the West will need to concern itself with the differences in technological history between the West and the Rest. While these differences were not the only ones that explain the meteoric material and political success of Western Europe in the nineteenth century, they constitute the most obvious and visible contrast. This dimension of global history has been brilliantly depicted by Daniel Headrick.[6] It would be rash to attribute *all* of Europe's dominant position to technology: institutions, geography, culture, and attitudes broadly defined obviously played a role as well. But technological gaps were concrete, palpable, and stark. There was no arguing with the advantages of steam-driven gunboats, telegraph, steel, chemicals, electricity, internal combustion engines, and the economic and political edge they implied.

Things had not always been that way. Europe's technological advantage over the rest of the world in the sixteenth century was at best tentative: half a century before the great discoveries, Chinese seafaring junks easily rivaled the best ships the Europeans had, and in terms of military technology, metalworking, and textiles, Europe was as much an imitator as a model to be imitated. The first Industrial Revolution changed all that, and while in the longer term Europe's ability to exploit its technological advantages for purposes of

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[6] Daniel Headrick,. *The Tools of Empire*. New York: Oxford University Press.1981.

political domination were to be ephemeral, there can be little doubt that in terms of technology it became the leader that non-Europeans emulated. That raises the hard question whether the technological advances that catapulted Western Civilization to the dominant position it held in 1914 (and, in many ways, still in 2000) were themselves inevitable or contingent. Technology is knowledge, and if we are to make sense of its evolution over time, we have to deal with it in those terms.

A standard argument in the canonical history of knowledge, associated above all with the work of sociologists of science such as S.C. Gilfillan and Robert K. Merton, is that progress in knowledge, whether scientific, technological, or other, is largely deterministic. That is, the growth of science and technology developed by a rational dynamic that made discoveries and inventions inevitable.[7] This dynamic consists of "external forces" such as the socio-political environment, relative prices, institutions, and so on, and "internal forces" in which knowledge moves by means of an evolutionary momentum of continuous development along historically contingent trajectories. While these "internal" forces may seem indeterminate to some extent, in effect they are often portrayed as equally deterministic. The main supporting evidence is the phenomenon of apparent independent duplication, which demonstrates ostensibly that if one individual had not discovered a particular idea or made a given invention, somebody else would have.[8] In this view the "impersonal" (deep underlying social and economic) forces of history determined the course of technological progress. Had James Watt never been born, by this account, the history of steam power and the Industrial Revolution would have been only marginally different. Had Henry Ford never lived, the cheap mass-produced car would still have been produced. History is stronger than people, or, as Thomas put it, it was the play that mattered, not the

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[7] See Robert K. Merton 1961. "Singletons and Multiples in Scientific Discovery," *Proceedings of the American Philosophical Society*, vol. 105. (1961) and S.C. Gilfillan, 1935. The Sociology of Invention. Cambridge, MA: MIT Press. (1935). The dated but still excellent literature survey in A.E. Musson "Editor's Introduction" in Musson, A.E., ed., *Science, Technology and Economic Growth in the Eighteenth Century.* London: Methuen. (1972) remains the best place to start examining this literature.

[8] The seminal sociological paper making this point was by W.F. Ogburn and D. Thomas. "Are Inventions Inevitable? A note on Social Evolution" *Political Science Quarterly* Vol 37.1922, although the phenomenon had been discerned much earlier. See Merton, "Singletons".

actors.[9] Counterfactual analysis in such a set-up would confirm that the path of technology is inexorable and the equilibrium steady state is unique and stable. There would still have been cheap steel without Bessemer and in all likelihood aspirin without Felix Hoffman.

That an "inevitability" of technological progress is implied by the lists of multiple inventions and discoveries is an overly simplistic inference and it answers the wrong question. To turn Thomas's metaphor around, the actors may not have mattered, but there would be no *Macbeth* without the playwright. Every discovery and invention is made by an individual conditional on a certain background knowledge. It is not the individual who is necessarily indispensable but the background knowledge to which he or she has access. This knowledge determines the likelihood of a discovery being made. We tend to think of the inventors as "accidental" but somehow the necessary knowledge they possess to formulate the question and find the answer is assumed to be given. Is this the correct approach? How inevitable is the emergence of this knowledge? To phrase it differently, the question should not be "had Edison never lived, would we have had an incandescent lightbulb?" but rather "had the Western world never discovered electricity, would non-Western cultures eventually have developed the incandescent lightbulb"? My answer to this question is basically negative. Western knowledge of nature was neither "better" nor "deeper" than the beliefs of the Chinese, the Africans, or the Aztecs. But, as I shall argue, it was *different* to the point that had the West never existed, humanity would probably never have seen digital computers, antibiotics, or nuclear reactors.

A counterfactual of "what would the world have looked like without the Industrial Revolution in the West" would not preclude economic growth. Growth can emerge from the establishment of and gains of trade, from better government and institutions, from the gains due to improved allocation, mobility and economic freedom, and from the accumulation of capital. Yet it is hard to believe that without the technological breakthroughs of the past two centuries, economic growth would have been sustained. The

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[9] Thomas, "The Automobile Industry," p. 140.

twentieth century was not the first century in which growth of any kind occurred, but degree is everything here, and, as many scholars have emphasized, the rates of growth in the twentieth century differed enormously from those in the more remote past.[10] Without the Industrial Revolution and the subsequent events, the world would have settled into an economic trajectory in which trade and good government might lead to periods of feeble (by our standards) growth, to be undone by wars or Malthusian pressures. Technological change would not have come to dominate income levels.

Phrasing the question as an explicitly counterfactual statement is, at some level, a purely rhetorical device. But it is an effective one. Areas that have rejected Western influences such as Afghanistan, North Korea, or Burma, or areas that have for one reason or another not been able to absorb much of it (say, in Papua New Guinea) have perhaps been fortunate in terms of preserving what they regard as their unique culture. But they have done so at a staggering price in terms of material well-being. These countries illustrate in vivid color what the entire world might have looked like had the "West never Risen." We do not have to imagine the counterfactual world: some parts of our actual world are a fair approximation.[11] My argument is that what made the West is neither efficient institutions nor capitalism (other economies had them), but its tendency to understand, control, and exploit natural phenomena and regularities in a different way. The advantage of a counterfactual is well put by Cowan and Foray: the persuasiveness of a counterfactual lies in our ability to infer the consequent from the antecedent, by establishing a relationship between the two.[12] In much of the counterfactual analysis in economic history, classical price theory provided the theory that

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[10] For a recent restatement, see, J. Bradford DeLong. "Cornucopia: The Pace of Economic Growth in the Twentieth century." NBER Working Papers, 7602. 2000.

[11] I should add the obvious caveats that such regions are selected and thus not representative of what, say Japan or Taiwan would have looked like, and that even in those countries which have avoided Western influence, the impact of the West and the negative reaction to it obviously contaminate the experiment.

[12] Robin Cowan and Dominique Foray, " Evolutionary Economics and the Counterfactual Threat" Unpublished paper, MERIT (University of Maastricht) and IMRI (Université Dauphine). 1999.

allowed us to do this.[13] A "theory of useful knowledge" is not nearly as well developed, but in important historical questions we have to make do with what there is.

The "knowledge of nature" is thus central to my argument. To make things a bit more precise we may distinguish between *instructional knowledge* or *techniques* (which I shall call 8 knowledge), and their epistemic basis in *useful knowledge* (S knowledge).[14] Techniques are instructions (implicit or explicit) on how to go about manipulating natural phenomena and regularities for the material benefit of people, much like instructions in computer programs, recipes in cookbooks, and "how to" manuals. Useful knowledge consists of the awareness of natural phenomena and regularities that underlie the instructions that constitute a technique. It is far larger than what we normally include in "science" – it includes basic understanding of mechanics and energy, principles of engineering practice such as fulcrum-and-levers, winches, pulleys, as well as geography, the behavior of plants and animals, geography, the properties of materials, "old-wives tales" and similar pieces of knowledge. Techniques thus depend on *some* prior knowledge of nature, which I will call their *epistemic base*. Without such a base, a technique could exist no more than a particular protein being expressed without a gene.[15] While these bases are never complete (in the sense that the natural phenomenon is never *wholly* understood), their size tends to be one of the determinants of the likelihood of the invention occurring. In the limit, a base can be so narrow that it consists of only one element namely "technique 8_i

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[13] The most famous example being Robert Fogel, *Railroads and American Economic growth*. Baltimore: Johns Hopkins Press, 1964.

[14] The term "useful knowledge" -- first proposed by Kuznets, is elaborated in some measure below. For a more detailed discussion see Joel Mokyr, "Science, Technology, and Knowledge: What Historians can learn from an evolutionary approach." Max Planck Institute on Evolutionary Economics Working Papers 9803, 1998 and *id.* "Knowledge, Technology, and Economic Growth During the Industrial Revolution." in Bart Van Ark, Simon K. Kuipers, and Gerard Kuper, eds., *Productivity, Technology and Economic Growth.* The Hague: Kluwert Academic Press, 2000, pp. 253-292.

[15] Formally, this is not quite accurate, since beavers may build dams and bees hives although, as far as we can tell, there is no "knowledge" underlying these techniques.

works."[16] I have termed such techniques "singleton techniques" in that their domain is a singleton. These techniques are normally discovered by accident or serendipity, and while their impact can at times be significant, further refinements and adaptations tend to be limited and soon run into diminishing returns. This is a commonplace observation: the better we understand a particular natural phenomenon, the easier it is to search in some specific and purposeful way for an improvement or an adaptation to changing circumstances and the more plausible it is that technological change becomes sustained and self-reinforcing.

To fully comprehend the ex ante indeterminacy of technological history we need to face three separate sources of contingency. First, how inevitable is it that useful knowledge itself emerges? Second, how inevitable is it that such knowledge, once it exists, will be mapped into techniques? Third, given the existence of a menu of techniques, how likely is it for a given technique to be selected? To come to grips with that triplet of questions we need to formulate, however superficially, some theoretical framework that allows us to understand how useful knowledge evolves over time. As I have indicated elsewhere (Mokyr, 1998), an evolutionary framework of some kind, which is by construction non-determinist and selectionist, seems appropriate to a historical understanding of technological knowledge.

Is the indeterminacy of technological history damaging to counterfactual analysis? Cowan and Foray correctly point out that precisely because evolutionary theory is rich enough to realize that history can produce a lot of different outcomes, its predictions are not very tight and counterfactual analysis runs the risk of not being very compelling. Insofar that we are trying to explain a minor technological feature this is perhaps true. But in the larger picture, evolutionary counterfactuals seem to make sense even in a highly indeterminate world, provided we are not too specific. For instance, Stephen Jay Gould famously asked if we rewound and replayed life's tape, whether the history of life would look the same, and answered in a resounding negative.[17]

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[16] To be logically consistent, the complete "catalog" of techniques in 8 is part of S.

[17] Stephen Jay Gould, Wonderful Life: *The Burgess Shale and the Nature of History.* New York: W.W. Norton.1989, p. 48.

Others have not been so sure, but the phrasing of the question clearly suggests the obvious attractive rhetoric of the counterfactual in evolutionary tales. In Cowan and Foray's terminology, what Gould is suggesting is a "weak" counterfactual, one that identifies important events that foreclosed certain options. If History is a branching process, consisting of a huge number of bifurcations, the present has been produced by an endless set of decisions on paths not taken. By identifying the branching points, as they note (p. 16), we can show "why the economy followed the route it did." In the final analysis the counterfactual tale serves not as a means of prediction or a normative assessment of where we are relative to where we could have been, but as a pedagogical tool to understand why the world is as it is. Its weaknesses are that I cannot be very specific about the alternative paths that would have been taken. All I can assert is that the actual world was not the only possible one, and speculate about the point in History where other branches would have clearly led to a very different outcome. In the final analysis counterfactual analysis serves not as a means of prediction or a normative assessment of where we are relative to where we could have been, but as a pedagogical tool to understand the world as it is.

An Evolutionary View of the History of Technology

The concept of looking at human ideas and knowledge in a Darwinian set-up is quite natural and has occurred to many scholars. The innovation that Charles Darwin proposed was not just to show that species had descended from other species, but more basically that historical processes could be described through a mechanism of random mutation and non-random selection. In the words of ultra-Darwinists, it was this notion that constituted "Darwin's Dangerous idea."[18] Philosophers of science, following the pathbreaking work of Donald Campbell have been refining notions of evolutionary epistemology and its implications for the

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[18] Daniel Dennett, *Darwin's Dangerous Idea: Evolution and the Meanings of Life.* New York: Simon and Schuster, 1995.

history of science.[19] The idea is simple: new technological ideas, like mutations, are highly stochastic. In a world in which inventions are based on very narrow epistemic bases, and in which serendipity played a predominant role, selection would be the only force that provided directionality to this process. In a world in which inventions are based on a deeper understanding of nature, new technology would be in part the result of a deliberate purposeful *search* for new forms (a search that never occurs in nature). Yet even then, unless such knowledge could become so deep that it infallibly yields the desired results, there will be a randomness (or, better put, a blindness) in the process that generates innovation which requires post invention selection.

The advantages of an evolutionary approach to the "history of knowledge" have been widely discussed and need not be restated here.[20] Two points are worth noting however. The hard question of contingency vs destiny comes up with *both* S-knowledge and 8-knowledge. The issue can be well-illustrated by the following example: the discovery of America by Europeans was one of the greatest additions to the S-set of the West in history. Conditional on the technological advances in shipbuilding and navigation in the fifteenth century, and European greed and curiosity, it is reasonable to think that the discovery itself -- as opposed to its precise timing -- was inevitable: had Columbus not made the journey (or decided to take the Vasco Da Gama route), sooner or later someone else would have made the journey and America would still have been there in exactly the same location. Had the Europeans by 1490 not advanced their maritime skills relative to the ancient Greeks, the discovery seems less probable (if not impossible).[21] Yet, even had they

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[19] Donald T. Campbell, "Blind Variation and Selective Retention in Creative Thought as in Other Knowledge Processes." In *Evolutionary Epistemology, Rationality, and the Sociology of Knowledge* edited by Gerard Radnitzky and W.W. Bartley III, 91-114. La Salle, Ill.: Open Court, 1987 (orig. published in 1960). Michael Bradie, "Assessing Evolutionary Epistemology." *Biology and Philosophy*, Vol. 1, No. 4, 1986, pp. 401-459; Franz Wuketits, *Evolutionary Epistemology and Its Implications for Humankind*. Albany: SUNY Press, 1990; Kai Hahlweg, and C.A. Hooker, eds. Issues in Evolutionary Epistemology. Albany: SUNY Press, 1989.

[20] Richard Nelson, "Recent Evolutionary Theorizing About Economic Change," *Journal of Economic Literature*, Vol. XXXIII (March 1995), pp. 48-90; John Ziman, "Selectionism and Complexity." in John Ziman, ed., *Technological Innovation as an Evolutionary Process.* Cambridge: Cambridge University Press, pp.41-51.

[21] Hindsight bias is perhaps at play here: we know that the Greeks and Romans did not discover America, and while Vikings and probably Basques got to the North American coast, this knowledge did not become accessible to many others. Hence the most

never found the route, America would still be there.

Is the same true, say, for the laws of physics and chemistry, for our understanding of infectious disease, indeed for the theory of evolution itself? Are most natural laws and regularities "facts" that await our discovery, and that sooner or later will become part of S simply because they are "true"? Or are they, as many modern scholars in the humanities assert, social constructs much like the American constitution or the rules of basketball? Would another society have discovered a very different way of looking at nature, one that would not have led to relativity and quantum theory and microbiology but to something entirely different, unimaginable but possibly equally able to explain the observable world around us and map them into techniques that are widely used? This is one of the trickiest questions in the philosophy of science and I am not going to solve it here. But one factor persuading us that knowledge is really "there" and is not just what Cohen and Stewart call a "brain pun," is that our knowledge of nature maps into techniques that work visibly: chemistry works – it makes nylon tights and polyethylene sheets.[22] Physics works – airplanes fly and pressure cookers cook rice. Every time. Strictly speaking, this is not a correct inference, because a functional technique could be mapped from knowledge that turns out to be false.

The second point about evolutionary theory as a historical tool is that it explains the form of creatures not in terms of their "DNA" but in terms of their historical development within a changing environment. A Newtonian explanation of why "an entity" is what it is is time independent. In one witty formulation, God gave the easy problems to the physicists.[23] Open, time-variant systems such as evolution do not lend themselves to precise formulations that predict accurately, given only sufficient boundary conditions.

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acceptable assessment would be that had the technology not advanced, the discovery might still have occurred, but with lower likelihood.

[22] Jack Cohen and Ian Stewart, *The Collapse of Chaos: Discovering Simplicity in a Complex World*. Harmondsworth: Penguin.1994, p. 54.

[23] Richard Ned Lebow, Janice Gross Stein, Steven Weber, and Steven Bernstein,. "God Gave Physics the Easy problems: Adapting Social Science to an Unpredictable World." *European Journal of International Relations* Vol. 6, No. 1 (2000) pp. 43-76.

Moreover, as Ziman has pointed out, whereas closed systems such as physics tend to be statistical in that they reflect *expected* values, evolutionary systems – of any kind – tend to amplify *rare* events (such as successful mutations or brilliant ideas).[24] Because these "rare" events are themselves not inexorable, and because it is unknown *which* of them will actually be amplified as opposed to being rejected by the selection process for one reason or another, they infuse an irrepressible element of indeterminacy into the system. Changes in the environment will induce adaptation in some species and lead to extinction in others, but there seems to be no foolproof rule that indicates when one or the other outcome will prevail. A counterfactual analysis can then proceed under the assumption that a "rare event" that did in fact occur did not happen. What it cannot do with any persuasion is to replace it with another rare event that did *not* happen since we cannot really pick one from another one just as (un)likely.

Thus far, most scholars working in this area have tended to apply evolutionary epistemology more to science than to technology.[25] A more complete description of the logical building blocks of an evolutionary epistemology of technological knowledge is given elsewhere.[26] It is worth pointing out here that a strict Darwinian analogy is partial at best and misleading at worst. Above all, "natural selection" through some kind of fitness criterion is only a *metaphor* in evolutionary biology. Nobody, of course, does any real selecting. In evolutionary epistemology this is not the case: there is conscious selecting. The "choice" of technique is a reality for every engineer, every farmer, every artisan, every homemaker. Choosing a technique is costly in that at the very least involves an opportunity cost, and often it involves real resources.

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[24] Ziman, "Selection and Complexity."

[25] For some exceptions, see Edward Constant, *The Origins of the Turbojet Revolution*. Baltimore: Johns Hopkins Press, 1980. Walter Vincenti, *What Engineers Know and How They Know It.* Baltimore: Johns Hopkins Press, 1990 and the essays in Ziman, *Technological Innovation*.

[26] See Mokyr, "Science, Technology, and Knowledge"; *id.,* "Evolutionary Biology, Technological Change, and Economic History." *Bulletin of Economic Research*. Vol. 43, No. 2 (April 1991), pp. 127-149. *id.,* "Evolution and Technological Change: a new Metaphor for Economic History?" in Robert Fox, ed., *Technological Change* London: Harwood publishers, 1996, pp. 63-83.

The underlying S knowledge is also subject to selection, but here the concept is less sharp. Selection may be viewed as the process in which some people choose to *believe* certain theories and regularities about natural phenomena and reject others. This is the way evolutionary epistemology thinks of it[27]. Alternatively, we may think of knowledge being stored in people's minds and storage devices, but some knowledge is being discarded because of positive storage costs. Those two types of selection do not wholly coincide. Historians of science preserve knowledge of discredited theories, while some knowledge is believed to be "true" but sufficiently trivial to be discarded.

In any event, this set-up places the central issue of technological history in sharper focus. An evolutionary theory cannot predict with any accuracy what knowledge will appear any more than a biologist can predict what mutations can appear. It can however rule out the emergence of techniques which require an epistemic base that does not exist at that time, and it predicts that when techniques emerge as singleton or narrow-based techniques, they are likely to become dead-ends rather than the basis for a technological trajectory. It also implies that the emergence of a potential knowledge base for a set of techniques is never *sufficient* for technological advances to emerge, since there is nothing to guarantee that this knowledge will be actually used for anything. In short, an evolutionary approach suggests leaving the tight and neat world of sufficient or necessary conditions and takes us into the messy world of Darwinian thinking, a world full of contingency and chance.

The question I take on with this approach is whether every technique that existed had to be and whether techniques that are not observed could not have been. In any Darwinian system, either in a world of living creatures or one of technological options, selection can take place only if the *raw materials* on which the choices occur exist. The Weismannian orthodoxy implies that we cannot predict what kind of mutation will occur in nature and thus we cannot understand fully why some traits develop and not others.

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[27] The *opus classicus* here is clearly David Hull, *Science as a Process.* Chicago: University of Chicago Press, 1988.

Understanding what we observe begins with asking why there are things we do not observe, and this is of course the way to approach counterfactual history. The answer to the question above begins with the fundamental distinction between species that are not observed because they were selected against, those that are not observed because the mutations that would have brought them along never came about, and those that could never be except in our imagination because they violate some law of physics.[28] Thus current biologists distinguish, with some inevitable gray areas and ambiguity, five existing "kingdoms" of living beings, and about 16 important phyla of the Kingdom Animalia or Metazoa. But some phyla that *could* have existed today because they did at some point in the past are no longer there.[29] Given the important role of chance in the extinction of species, this in and of itself suffices to drive home the point that accidents play a major role in any kind of evolutionary tale of the past.

To illustrate this logic, I follow Dennett who distinguishes various levels of "could have been" compared to the actual. Dennett points out the difference between the logically impossible and the physically impossible.[30] Similarly, certain life forms are physically impossible, such as insects the size of elephants. Beyond that, there are life forms that are physically possible but biologically impossible in the sense that there is no evidence that anything even remotely similar ever emerged, such as flying horses (Dennett's example). At a further level there are life forms that were biologically possible, but apparently never emerged such as flying marsupials or legged snails. Finally there are forms of life that existed much like the species in the Burgess Shale but were "selected against" and are today extinct. As Dennett recognizes, there are pitfalls

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[28] Mark Ridley, *The Problem of Evolution*. Oxford: Oxford University Press, 1985, pp. 55-56.

[29] A glance at the phyla that did at some point exist was provided by the celebrated Burgess Shale. Gould in his *Wonderful World* has maintained that fifteen or twenty extinct organisms unearthed there "deserve" by the distinctness of their anatomy alone the rank of a separate phylum. Regardless of what other biologists think of this claim, given the unusual circumstances of the Burgess Shale, one has to concede that the diversity of actual life on earth may exceed anything we deem possible.

[30] Dennett, *Darwin's Dangerous Idea,* ch. 5. In Dennett's words, Superman who flies faster than the speed of light is logically possible but physically impossible; Duperman who flies faster than the speed of light and stays in the same place is even logically impossible.

in these distinctions (the differences between physically and biologically impossible are fuzzy, and extinction could have many causes besides having been negatively selected), but for our purposes such a hierarchy of the possible will be useful to study the difference between actual and possible techniques.

Consider the universe of techniques, illustrated in fig. 1. First, because we are dealing with human knowledge, we have to subscript almost everything with t. The largest meta-set which is timeless (but also therefore rather meaningless) is that of *imaginable* techniques. This includes all techniques that could conceivably be concocted by the human mind. The dimensions of this set are huge but in the final analysis it is constrained by the limitations of the human mind. Smaller and wholly contained in this set of techniques ever *imagined* until time t. This is an expanding set, since new science fiction novels and starry-eyed engineering students dream up new techniques every day. Another subset of the imaginable techniques is the set of *imaginable and possible* techniques, that is, those that are not contradicted by the laws of nature (as we understand them today). This set is not quite identical to the set *believed to be possible* at any time t. Today (t = T) we believe that travel at speeds exceeding the speed of light, transforming lead into gold by chemical means, creating a perfect perpetuum mobile, and the passing of acquired characteristics through animal breeding are not possible, yet people at various times in the past believed such techniques to be possible and spent resources trying to develop them. At the same time, we today believe that we can concoct substances that will cure strep infections such as puerperal fever in a few days. In principle, the set of possible techniques is fixed, but because human knowledge is imperfect, in practice we define “possible” as “believed to be possible at our time (T).” We cannot be certain that the two are identical -- in fact, we can be sure they are not -- , but it is by definition the best we can do right now.

A subset of the set of techniques possible to the best of *our* knowledge (at t=T), and possible at time t # T in the sense that they were within the technological capabilities of the age is the set of *potential* techniques at time t. A subset of that set is the set of *feasible* techniques, that is, the intersection of the potential at t with the "imagined" at t set, techniques that are not only possible and within the technological capabilities of the time, but also were imagined by someone.[31] Feasible techniques have the minimum epistemic base necessary to write out the instructions fully. Within the feasible set lies the *realizable* set. Feasible techniques may not be realizable because even though the epistemic base to write out the instructions that comprise the technique exists, there is too little complementary knowledge necessary to carry it out on a significant scale.[32] Another cause could be some blocking element such as the physical absence of a crucial ingredient (say, a society may fully know how to make atom bombs but cannot lay its hands on enriched plutonium). More commonly, they are not realized because of social prejudice, superstition, resistance of vested interests, or because the idea does not "catch on," for instance when the full benefits of the technique are underestimated.

Selection occurs at this level. The set of feasible techniques constitutes the "menu" from which selection occurs. The set of *actual* techniques in use, those that are actually selected, is a subset of the realizable set. Another subset of the realizable techniques is the set of *rational* techniques. These techniques dominate other techniques in their ability to satisfy whatever objective function we impose, equivalent to the unit isoquant in economics. Finally, there is a set of *optimal* techniques (a subset of the rational techniques), which is that segment of the rational set that is best suited to any given environment, although this requires a precise definition of what "best suited" means. Note that an area like M in fig. 1 means here a set of

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[31] Note that the "Imagined and possible" set includes a large component that could not be achieved by the technological means of the time and hence is not in the feasible set. Roger Bacon, Guy de Vigevano, Francesco di Giorgio Martini and for that matter Jules Verne all imagined techniques that were beyond the reach of their times, so they were in the potential but not the feasible sets. Bertrand Gille points out that mechanization was in part the result of a "speculative type of thinking; Da Vinci was not the least of its representatives." See Bertrand Gille, "The Fifteenth and Sixteenth Centuries in the Western World." In Maurice Daumas, ed., *A History of Technology and Invention*. New York: Crown, 1969, p. 42. At the same time we can think of many examples of techniques that were quite within the technical potential of certain societies but simply never occurred to anyone before. Once seen, they were embraced with enthusiasm. One thinks of wheelbarrows and spectacles (invented in the middle ages) or barbed wire and anaesthesia (invented in the mid nineteenth century).

[32] The knowledge necessary to invent a technique to build an artifact such as a piano or a bicycle might be quite different than the knowledge necessary to actually use it.

techniques that are possible and imaginable but never occurred to anyone, perhaps because the kind of societies that were able to produce them did not have a chance to get to that point. I shall return to this idea at the end of this paper.

The history of technology is largely about how we get from potential techniques to feasible techniques -- that is, which of the techniques possible to a society actually occurred to anyone –, the transformation of a number of feasible techniques to realizable ones, and the emergence of the actual historical techniques that were selected, put into use and are observed by economic historians. There should, however, be a fair amount of interest in techniques that could have emerged but did not, or techniques that could have emerged much earlier than they did. Counterfactual history here is handicapped by the hindsight bias, that is, we know which techniques occurred historically, and for that reason they seem more plausible than others.[33] Techniques that did not occur but can be imagined are written off as science fiction. Even techniques that were tried briefly but then were selected against are normally dismissed as obviously inferior to those techniques that were eventually selected. The dirigible and the electrical car, to pick two obvious examples, are normally dismissed not only as "never were" but also as "never could have been."

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[33] Lebow, "Franz Ferdinand."

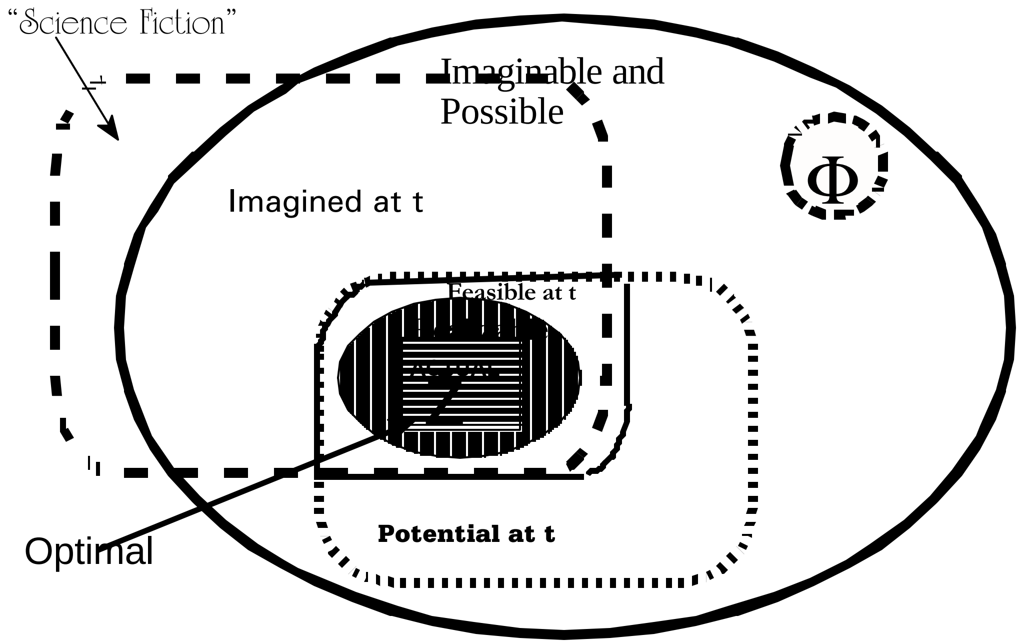

Figure 1: Metasets of techniques

We can then picture the evolution of techniques as the result of the co-evolution of two separate Darwinian systems. One is the growth of the knowledge base S itself, in terms of discoveries in science, geography, the gradual accumulation of applied engineering and farming knowledge in terms of what works where, and the thousands of little anonymous pieces of experience knowledge ("microinventions") that together make production more efficient over time even in the absence of scientific breakthroughs. The other is the growth of the techniques implied by that knowledge. These two systems interact in subtle ways. In some regards it resembles the evolution of systems of living beings: phenotypes, much like techniques, depend on changes in the genotype to develop radically new forms. Much evolutionary change occurs through "adaptation" that is, the activation of hitherto inert genetic material activated because of changes in the environment. Unlike biological systems, however, knowledge systems allow feedback from the system of "doing" to the system of "knowing." Substantial advances are made in knowledge when new tools (that is techniques) permit the accumulation of more knowledge. Thus the shipping and navigation technology of the fifteenth century made the geographical discoveries of the sixteenth possible, just as the improved microscope (see below) prepared the ground for the discoveries of Pasteur and Koch.

If the argument made above here is correct, the counterfactual to the "Rise of the West" is that if it had not happened in the West, it probably would not have happened anywhere or at least not in any form remotely resembling the industrial development of the West (and eventually the world) as it took place. What is striking about the economic history of the modern era is not just the great advances in steam, iron, textiles and engineering in the closing third of the eighteenth century, but the *continuation* of the inventive activity after 1815 or 1820, when the *sturm und drang* of the first Industrial Revolution had apparently spent themselves. Such sustainability would not and could not have been attained without a widening epistemic base. Yet this runs counter to the widely-held view that Western science contributed little directly to the first Industrial Revolution and its aftermath. I shall return to this issue at the end of this paper.

The Epistemic Bases of techniques

Apart from entertainment, imaginable but infeasible entities such as King Kong or cold fusion seem to serve little purpose. They illustrate, however, that the set of feasible techniques is a function of time. For instance, directed human flight in heavier-than-air machines must be considered in the "ever imagined" but infeasible set until 1903. Yet when techniques are being imagined, do the imaginers rule them out as fun but impossible, or do they attach some non-zero probability to the event ever becoming a reality? Much of modern science fiction literature must in its heart of hearts realize that many of the techniques imagined are simply impossible *by today's knowledge*. An example is traveling at speeds exceeding the speed of light and thus venturing far outside the solar system. Cold fusion is a somewhat different matter: while the claim was received with great scepticism, it was admitted that experimental methods were needed to confirm it since our knowledge was inadequate to rule it out a priori. In this sense it is different from perpetuum mobile machines. Yet such categories are all time-variant and depend on knowledge at a specific point. The idea of the "fountain of youth" would probably be in the "impossible" category half a century ago, but now seems to have shifted categories with research in the "ageing genes."

A large number of techniques that eventually arise are first imagined, then understood to be possible, and finally realized. Many others remain dreams and never penetrate to the inner circles of fig. 1 either because they are impossible (the stone of the wise) or just not feasible at that particular t (human flight). Roger Bacon (1220-92), to cite just the most famous example, described gunpowder and spectacles which both became feasible in his own age. He also insisted on the possibility of mechanically propelled carriages and ships, and hot-air balloons. Informed technological speculation has always been and has remained an inspiration to actual progress. While precise linkages cannot be demonstrated, Gille concludes that in his survey of Renaissance technology that "the growth of mechanization also appears to have been in large measure the result of a speculative type of thinking... before their practical applications were discovered, machines were created for their intellectual amusement."[34] Many of the great Renaissance *Compendia* ("theaters") of machines were lavishly illustrated "imaginative excursions" into what might be.[35]. Ferguson argues that such imagination contained the "seeds of the explosive expansion of technology in the West".[36]

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[34] Gille, "The Fifteenth" p. 42.

[35] In 1588, for instance, Angostino Ramelli published *Le Diverse et Artifiose Machine* full of lavish pictures of cranes, sawmills, hurling engines and other devices nobody had ever seen. Yet Ramelli clearly described what he thought was possible.

[36] Eugene Ferguson, *Engineering and the Mind's Eye*. Cambridge: MIT Press, 1992, pp. 115, 120. It is not precisely clear what effect the writings of someone like Jules Verne had on the actual development of technology, but the notion that his *20,000 Leagues* inspired some developments in submarine construction is attested by the fact that in 1886 Andrew Campbell and James Ash of England built a submarine driven by electric motors powered by a storage battery and named it *Nautilus*; the idea of running it by an internal combustion engine while on the surface and electric motors while submerged became the standard for the industry.

All the same, the fact that a machine or any kind of device can be *imagined* is only one small part of technological history. What is the boundary between a technique that is *imagined and possible* (by our standards), one that is *feasible*, that is, within the technological capability of a society to build, and one that is *realizable*, that is, can be activated in production? While the Dutch inventor Cornelis Drebbel actually succeeded in building a prototype of a submarine in 1620, there was no chance of it ever becoming a reality before the advent of electrical power and invention of the internal combustion engine.[37] Pascal and Leibniz imagined and design calculating machines, but the engineers of their time simply were unable to construct the parts to make such machines within reach. They were feasible, but not realizable. In Jules Verne's days, knowledge of metallurgy, engineering, and electricity had advanced a great deal beyond 1620. Realizability requires an epistemic base sufficient to write out the instructions fully and the ability (that is, human capital) to carry them out and make them an *economic* reality so that they can be made at an affordable price.

As noted above*, any* technique in use requires an epistemic base, that is, sufficient relevant knowledge about the underlying exploitable regularities of nature. Even an ancient farmer with no knowledge whatsoever of soil chemistry, plant genetics, pests, hydraulics, and so forth, needed to know certain basic regularities about the weather, water control, seeds, soil manipulation and so on if he was to produce a crop. Through most of recorded history people produced chemicals without chemistry, smelted, refined iron without metallurgy, and bred animals and plants without genetics. Techniques differed in the width of epistemic base they required to become feasible. For thousands of years people used fertilizers without knowing anything about soil chemistry, and water power without fully working out the laws of hydraulics. However, an age that did not understand electricity at all could not build generators.

Yet while the knowledge bases in the more remote past were thus very narrow, they still existed. It

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[37] The Drebbel submarine was inspired by a 1578 tract by an English writer named William Bourne and his design followed Bourne's description. It was made of greased leather, but remained a curiosum, the attempts by American shipbuilders such as David Bushnell's (whose *Turtle* was tried during the War of Independence) and Robert Fulton notwithstanding.

was recognized that pig iron mixed with wrought iron in some fashion produced, after much toil, an intermediate product of superior quality called steel. Animal refuse hauled to arable fields tended to improve crop yield. Breeding unusually big horses with other unusually big horses begat a line of large horses. Patients with contagious diseases were understood to infect other people through close contact. Even if their cause was not known, the regularities of high and low tides could be observed and exploited for navigation and tidal mills. If patterns and regularities could be discerned, no matter what the metaphysical interpretation people gave to them, they lent themselves to exploitation.

Two inferences can be made from this set-up. The first and most obvious is that if the necessary minimum S knowledge was lacking altogether, certain techniques would simply not develop. The second is that techniques that were created on a very narrow epistemic base would not be used properly and could not form the base of sustainable and continuous technological development.[38] It is the unique characteristic of modern European material civilization in the past three centuries that it has succeeded in creating a system in which S-knowledge and 8-knowledge continuously complement and reinforce each other. For sustained technological progress to take place it needs to have a large and growing knowledge base to support it. In part this is because the widening of epistemic bases increases the component of purposeful search and reduces the randomness of technological advances a little: knowing *why* something works prevents spending too much effort on dead-end projects that do not work.[39] This is not only true for new technologies but also for existing

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[38] Thus in the eighteenth century it was discovered that cinchona bark was an effective remedy against malaria without the slightest notion about the etiology of the disease or why and how cinchona bark and its active ingredient quinine worked. Yet it was known that it did, and thus the technique was used. In this case the entire knowledge on which the technique was based that "it worked". Cinchona use never led to an effective cure, let alone prevention, of malaria, and its widespread use against other fevers remained of course without any beneficial effects. The canning of food was discovered by Nicholas Appert in 1795, but because the underlying bacteriological principle was unknown, the food was prepared at super-optimal temperatures and therefore unappetizing and unpopular until the Pasteur Revolution of last third of the nineteenth century.

[39] Leonardo in a famous drawing showed the impossibility of perpetual motion by building a device that consisted of sticks with weights attached to them, and then pointing out that "no matter how much weight is attached to the wheel which weight causes the motion, doubtlessly the center of such a weight will stop at the pole and no instrument that human genius can invent can avoid such an effect" followed by "Oh, followers of continuous motion, how many varied geniuses you have created in such research. You

technologies that had existed earlier on a narrow base. Knowing more also allows for more recombination of technological knowledge, that is, the application of insights and regularities from other areas to projects and objectives that seemed hitherto unrelated.

Compare, for instance, the advances in power technology in the eighteenth century. As is often pointed out, the knowledge base of the steam engine did not include the principles of thermodynamics that predict its energy efficiency. The early pioneers did not fully realize what an engine is, which is a way to convert heat energy into work subject to the laws of thermodynamics. They did, however, rely on two important additions to useful knowledge that preceded it: the understanding of atmospheric pressure, discovered by Continental scientists such as Evangelista Torricelli and Otto von Guericke and the early seventeenth century notion that steam was evaporated water and that its condensation created a vacuum.[40] Between those two insights, the idea of an *engine* took shape. At the same time, however, experimental and theoretical hydraulics advanced continuously, and consequently much of the "action" in eighteenth century power technology took place in the remarkable improvement in water power, culminating in Smeaton's breast wheel and Fourneyron's water turbine. The gradual growth in the understanding of thermodynamics in the nineteenth century made the improvement of combustion engines of all kinds easier and allowed techniques to move in novel directions through the work of men like William Rankine.[41]

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belong to the same fold as those who seek gold (alchemists)." Cited by Marco Cianchi, *Leonardo's Machines*. Milan: Becocci Editore, 1984, p. 82.

[40] Usher has attributed this finding to Solomon De Caus, a French engineer and architect in a 1615 book. See A.P. Usher, *A History of Mechanical Inventions.* Cambridge, MA: Harvard University Press, 1954, p. 342. Uncharacteristically, Usher is inaccurate here: in 1601, Giambattista Della Porta already described a device based on the same idea, and both were apparently inspired by the appearance in 1575 of a translation of Hero of Alexandria's *Pneumatics* which, while not grasping either the notion of an atmospheric engine nor that of a condensation-induced vacuum, focused the attention on steam as a controllable substance. It is hard to imagine anyone reading Hero without realizing that steam was evaporated water and that upon condensation "the vapor returns to its original condition."

[41] Donald Cardwell, *From Watt to Clausius: The Rise of Thermodynamics in the Early Industrial Age.* Ithaca: Cornell University Press, 1971, pp. 186-238.

The emergence of an epistemic base is never a *sufficient* condition for technological change to occur. Many societies might investigate nature for its own sake, without the Baconian notion that the main purpose of that knowledge is to improve our material welfare through the control of natural forces. It is this part that makes counterfactual history in this area so perplexing. We can be practically sure that in an age that did not have microscopes, the germ theory of disease would not have occurred to anyone. But even given microscopes, was the germ theory inevitable the way America was inevitable? Furthermore, given that the germ theory was accepted, were the techniques it mapped into, including antibiotics, therefore inevitable?

Counterfactual technology

How likely was it for the techniques that we actually observe to have emerged and can we place probabilities on techniques we can imagine but which did not emerge? Defining such ex ante probabilities of events that actually occur is sensible if we know something about the entire distribution even if only one event has materialized.[42] Using something like a probability gets around the endless confusion of a sufficient condition (which sets a probability at unity if a condition is fulfilled) or a necessary condition (which sets a probability at zero if the condition is not met). But for most observers there are few necessary or sufficient conditions in economic history, since there are few factors that have no substitutes or need no complements. Moving in the continuum between "very likely" and "very unlikely" without categorically ruling anything in or out seems prima facie a more satisfying way to think about the likelihood of the emergence of new techniques.

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[42] If I win the Illinois lottery, I might say that the ex ante probability of this event was negligible even if it actually occurred and it is hard to say that it was inevitable. The event "it will snow in Chicago at least one day in January," may not be regarded as inevitable, but surely it is a high-probability event. Finally, if I say that yesterday I predicted that the sun will rise in the East at some time I pick from astronomical tables, the probability of that event was in fact indistinguishable from unity and counterfactual analysis makes no sense.

Historians have criticized attempts of trying to explain why something did *not* happen.[43] But a statement such as the ex ante probability of this event happening was low, while little more than a rephrasing, drives home that at least for some historical issues, some events did not happen because they had low ex ante probability. This does not mean they could not have happened, given enough time. But if they did not, there was not enough time. The question "why not" is not entirely out of place, especially if an event very similar to the event in question happened elsewhere.[44] It remains to be seen if such probabilities are in any sense a useful tool in the history of technology.

But all such probabilities need to be made conditional on something. It makes almost no sense to speak of unconditional probabilities, because the emergence of techniques depends on the epistemic base underlying them. Yet, as I noted above, the probability of a singleton technique emerging is not always zero, and it is equally possible for a knowledge base to exist without the technique ever emerging. We may write the probability of technique 8_i emerging conditional on its knowledge base S_i as $P(8_i{*}S_i)$. One problem is that they have to be defined over some unit of time to be meaningful: clearly, if $t\ 6\ 0$, $P(8)\ 6\ 0$, and if $t\ 6\ 4$, $P\ (8)\ 6\ P^*$. In what follows, I shall ignore this complication.

Clearly, there is an important difference between the unconditional probability of a technique being invented $P(8_i)$ and the conditional probability. To be exact, the ex ante probability of technique 8_i to emerge is identically

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[43] Nathan Sivin, "Why the Scientific Revolution did not take place in China – or didn't it?" in *Transformation and Tradition in the Sciences* edited by Everett Mendelsohn, Cambridge: Cambridge University Press. pp. 531-554; Lynn White,. "Review Essay on Joseph Needham's *Science and Civilization in China*". *Isis*, Vol. 75, No. 276, 1984. pp. 172-179.

[44] To ask why any historical event that seems a priori feasible (because it did happen elsewhere) did *not* take place, is useful analytically: why did Canada not have slavery? why did the U.S. not have a successful socialist movement? why did the Soviet Union fail to develop the microprocessor? These seem useful questions precisely because in comparable situations the event *did* take place.

$P(8_i) / P(8_i * S_i)\, P(S_i) + P(8_i * S*_i)\, P(S*_i)$ where $S*_i$ is the non-occurrence of S. A more general formulation of the same idea is

$P(8_i) / \underset{S_j}{\mathbf{3}} P(8_i * S_j)\, P(S_j)$ where S_j are all possible states of the world of useful knowledge.

It is immediate that if S_i is necessary for 8 to emerge ($P(8_i * S*_i) = 0$) and S_i is unlikely ($P(S_i\ .\ 0)$), then 8 is itself unlikely.

Further, by Bayes's theorem,

$P(8_i * S_i) = [P(S_i * 8_i)\, P(8_i)]/P(S_i)$, which can be re-arranged to yield

$$P(8_i) = P(S_i)P(8_i * S_i)/[P(S_i * 8_i)]$$

Which means that the unconditional probability of 8 is larger: (1) the more likely S, (2) the higher conditional probability of 8_i given S_i, and (3) the *lower* the probability that S_i exists given that we observe 8_i. The latter takes into account the chance that 8_i could emerge as a singleton technique. For example, Ptolemaic astronomy and fifteenth century Euclidian-based geometry may have been quite unlikely to emerge. But conditional on those pieces of knowledge having emerged, it was quite likely for a set of navigational tools to be developed and the road to the New World to be discovered even if the unconditional probability was low. It would have been unlikely to observe these techniques *without* a Euclidian geometry. Thus it makes no sense to ask whether the discovery of America was highly probable or not without making clear whether this probability is or is not conditional on knowledge such as the shipbuilding skills that made the three-masted *caravelles* possible or the knowledge that the world was spherical and not flat.[45] If the conditional probability was sufficiently high, we would observe multiple inventions if inventors have access to more or less the same knowledge base. Such multiple inventions would demonstrate not that inventions were inevitable, but only that

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[45] In his letters trying to persuade the King of Spain to bankroll his expedition, Columbus quoted the statement by the thirteenth century English monk Roger Bacon to the effect that because the earth was round, one could circumnavigate it.

given the state of knowledge they were highly probable. Even given a state of knowledge, however, the evolution of certain techniques is never inexorable, though we will have to see below what boundaries can be placed on the process.[46]

What, then, determines the state of knowledge? In part, knowledge depends itself on technology: our ability to observe and process what we observe into exploitable regularities is in part determined by technology itself. Without instruments, we would not able to see the moons of Jupiter or Tubercle bacilli. Technology also determined how accessible the existing knowledge is to those who do not have it. Finally, technology sets concrete challenges and puzzles to scientists and natural philosophers that focus their minds on specific problems. Beyond its interaction with 8, the growth of S has an internal dynamic logic that makes it conditional on some prior state. After all, S follows a Markov chain in that S_{t+1} is conditional on S_t. Like evolution, there is a great deal of persistence in the movement of the entities in question: the state in t+1 is equal to that in t plus some innovation term. The past strongly constrains the present by limiting the choices.[47] Inevitability might be a statement about a high value of $P[(S_{t+1})^* S_t]$ or it might be a statement about $P(8_i{}^* S_i)$. The former is a statement about the historical path of useful knowledge and the pace and direction of discovery.[48] The latter is a statement about mapping probability, that is, the likelihood that a given piece of useful knowledge will be applied.

For instance, between 1880 and 1900, bacteriologists discovered a new pathogenic germ about every two years because the Koch postulates and new experimental methodology they implied made it relatively

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[46] Much like homoplasy in nature, certain techniques might evolve from very different types of S knowledge and yet look quite similar. Without geometry and Ptolemaic astronomy the Chinese navigators were still able to find latitude at sea although it is unclear which instruments they used. See Joseph Needham, *Science and Civilization in China* Vol. 4 pt. 3: Civil Engineering and Nautics. Cambridge: Cambridge University Press, 1971, p. 567.

[47] Formally this means simply that if S follows a stochastic process $St+1 = St + ,_t$, the term $,_t$ is bound away from large values so that evolution cannot change too much at one time.

[48] From a long-term point of view, however, we may want to answer questions about $P[(S_t)^* S_{t-n}]$, that is, how likely was this door to be opened given that between t-n and t a whole sequence of other doors had to be opened one-by-one just to get there.

obvious.[49] Other discoveries occurred despite having low probability given what was known at that time. One could imagine that at certain junctures, given S_t, two options, say S_{t+1} and S'_{t+1} are equally probable. These would be bifurcation points at which useful knowledge picks one path for what may be rather poor reasons, but once chosen, this path conditions much of what is to follow. Above all, what this view of technological change as a stochastic process implies is that questions about "inexorability" or "contingency" crucially depend on the time frame chosen. Even a highly plausible chain looks less so when compounded over long periods: if we are looking at a ten-period chain for each of which $P[(S_{t+1})^{*}S_t] = .95$, $P[(S_{t+10})^{*}S_t] = .60$. The invention of the internal combustion engine by Otto in 1876 seems plausible given the new thermodynamics of the mid nineteenth century, but how "probable" was it given only the work of Huygens in the seventeenth century or given the work of medieval scientists such as Roger Bacon?

To understand why some techniques are observed in history and why other potential and even realizable techniques were not, we need to know more about the development of S. Here we find ourselves in the position of the biologists. There is an observable world, of contemporary and past forms of life that actually existed or exists. In addition, there is a set of "feasible" or "realizable" life forms that never emerged. Watching the famous tavern scene in the first "Star Wars" movie provides some kind of idea on the life forms we can imagine even though few of those fantastic creatures actually are "realizable" at least under terrestrial conditions (which of course is the point). All the same, some imaginable and possibly viable life forms never emerged because the mutations that created the genotypes for them never occurred although there is no a priori reason why they could not have. To be sure, an examination of the actual -- albeit often

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[49] In point of fact, the crucial event in all likelihood was the invention of the modern microscope by Joseph J. Lister (father of the surgeon) an amateur optician, whose revolutionary method of grinding lenses (around 1830) greatly improved image resolution by eliminating certain chromatic and spherical aberrations. Lister's method of combining the lenses of compound microscopes on the basis of theoretical reasoning rather than trial and error reduced average image distortion by a huge proportion, from 19 to 3 percent. Cf. Stanley Joel Reiser,. *Medicine and the Reign of Technology*. Cambridge: Cambridge University Press. 1978, p. 76. It provides a good example of the complementarity and mutual reinforcement of S knowledge and "practices" (that is, techniques).

in "niche" conditions -- shows how rich and surprising the "realizable" set of life is.[50]

There are equivalents of these life forms in human beliefs about nature. It is easy to point to a variety of contemporary "weird" beliefs in the "flat earth tradition," from astrology, ESP, Recovered Memory Syndrome, mega-vitamin diets, Dianetics, Reiki, to millenarian doomsday prophesies that are still being held and form the basis of human technological action.[51] Looking further in the past does nothing to reassure the historian that selection processes guarantee the survival of rational ideas and forms of knowledge that produced techniques that worked "best." It might seem that today, more than in any age, we choose techniques on the basis of results and costs only, but there are too many exceptions to this rule to feel very smug about this.[52]

Is it then conceivable that forms of knowledge could have developed, consistent with the laws of physics and chemistry as we understand them, that would have created technological societies quite different from our own? Some historical experiments can be pointed to in which useful knowledge developed independently of Western societies: the pre-Columbian societies in America, and to a lesser extent Africa and East Asia (which always had *some* contact with the West). Much like the marsupials of Australia, who, unconnected to placental-dominated Eurasia, differed from life forms in the Eurasian continent while solving similar problems, non-European societies developed different forms of knowledge that underlay their

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[50] Any of a hundred descriptions of "weird life-forms" will do. Consider the reproductive behavior of *Hippocampus Erectus* (the common sea horse) in which -- contrary to almost all other life forms -- the *male* carry the fertilized eggs in a brood pouch and then lay them much like all other species. A tropical frog, *Dendrobates,* observes the following division of labor: the mother lays her eggs and covers them. The father visits the site from time to time and urinates on the eggs to keep them moist. The mother then returns to carry the young tadpoles on her back, one by one, and deposits them in the branches of a tree, and visits them from time to time. If they survive, she lays a few infertile eggs for their nutrition. See Robert Wesson, *Beyond Natural Selection*. Cambridge, MA: MIT Press. 1991, p. 76. It is hard to imagine that this kind of trait is "inexorable" by any definition.

[51] Michael Shermer, *Why People Believe Weird Things: Pseudoscience, Superstition, and other Confusions of our Time*. New York: Freeman, 1997. Martin Gardner, *Science: Good, Bad, and Bogus*. Buffalo, N.Y.: Prometheus Books 1981.

[52] A striking example of this is the polygraph ("lie detector" machine) which is widely used by investigative agencies despite very dubious credentials and inadmissibility in courts of law. See Kenneth Alder, "To Tell the Truth: The Polygraph Exam and the Marketing of American Expertise," unpublished ms., Northwestern University.1998.

agriculture, medicine, energy use, materials, construction, textiles, and so on. It is hard to know whether the differences between pre-Columbian American or Chinese forms of S-knowledge and the West were due to accident or to the fact that they operated in different physical environments. To a large extent, however, the Chinese dualistic approach to universal truth known as *yin-yang* and its medical applications must be seen as representing an alternative path to the challenges of human health and disease rather than an adaptation to a specific Chinese environment.[53]

The course of the evolution of useful knowledge is hard to understand and impossible to predict. It is externalist in that it interacts in complex ways with its environment: institutions, values, relative prices, income, religious beliefs, and the physical parameters of a region. The environment sets the selection criteria by which techniques are chosen, but does not directly determine the menu of technological options. It is internalist in that people are inherently curious and ambitious men and women will expand the horizons of knowledge to satisfy their own and others' curiosity. Yet it retains an irreducible element of contingency and indeterminacy. It is this aspect of it, more than anything else, that makes it so irresistibly similar to biological evolution despite the obvious differences. Some viable life forms were wiped out because of the accident that they were invaded by a mutant or alien species that was more adapted to their particular environment or had sufficient flexibility to adapt quicker. Similarly, non-Western techniques might have evolved very differently and produced novel forms had they not been invaded by Western ones and had their evolutionary lives not been cut short.

The historian of China A.C. raises an interesting counterfactual question when he asks what would

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[53] Of course, it is also possible as Cohen and Stewart, *The End of Chaos,* p. 55 point out that there is a truly alien science whose knowledge is completely orthogonal to ours, and that knows things that never occurred to us and vice versa. Or, more disturbing, perhaps all of *our* physics has been led down the wrong path and some other civilization could have done it better, or just differently and achieved better results. Given the ability of the S knowledge underlying Western science today to map into techniques that actually work, such a view is unlikely to gain much acceptance today. All the same, we cannot dismiss the possibility that some future scientists will look at the science of the late twentieth century with the same disdain we reserve today for phlogistic chemistry.

have happened to the Scientific Revolution in Europe, had seventeenth century Europe been invaded by a culture that has plastics, electronics, and napalm. Had Western science not arrived in the way it did, it seems unlikely that something *similar* would have arisen in China or the Middle East and taken the rest of the world by storm.[54] As matters turned out, Chinese natural knowledge and medicine followed a very different path, a path that was terminated when for all intents and purposes Oriental science surrendered upon exposure to European science, much like the way indigenous flora and fauna were overwhelmed when exposed to European species after Europeans arrived in America and Australia.[55]

In some ways, then, the biological analogy is helpful to counterfactual analysis. We can point to environmental factors (e.g. radiation) that increase the *frequency* of mutations; but there is no known way of predicting *what* mutations will occur. Similarly, we can point to *economic* environments that are conducive in some ways to the emergence of new useful knowledge, and we can point to the institutions that encourage and aid enterprising and resourceful individuals to apply this knowledge to production. The questions why *a specific kind* of knowledge or another emerged is, however, hard to understand even with hindsight. Much in the development of knowledge in the past depended on the choice of "legitimate" topics of investigation and the rhetoric of scientific discourse (that is, what determines whether something is widely believed) and hence on the conventions of authority and expertise, and in general on the sociology of knowledge. The Scientific Revolution in the West formulated a conception of a rational and mechanistic universe which behaves according to certain rules and regularities, natural laws, that can be exploited. But this rationalistic approach was not the only way to approach the natural world (in fact, it may have been typical of the specifically European attitude) and itself was anything but an inevitable historical development.

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[54] A.C. Graham, "China, Europe, and the Origins of Modern Science: Needham's The Grand Titration. In Shigeru Nakayama and Nathan Sivin, eds., *Chinese Science: Explorations of an Ancient Tradition*. Cambridge, MA: MIT Press, 1973, p. 68.

[55] Alfred Crosby, *Ecological Imperialism: The Biological Expansion of Europe, 900-1900.* Cambridge: Cambridge University Press, 1986.

The growth of "useful knowledge" is therefore quite far from deterministic. Moreover, contingency is compounded by the indeterminacy of the selection mechanisms that retain new techniques for survival. In this respect, the analogy with evolutionary biology fails us badly. In living beings "fitness" has a precise meaning and in principle we can observe traits and assess whether they contribute to the likelihood of survival and reproduction. In the selection of techniques, the criteria for selection are to a large extent socially and culturally determined. In a "pure" economic world, to be sure, contribution to profits might be the only selection criterion. But very few economies ever operated that way. Techniques were selected or rejected for a variety of reasons, which themselves were contingent. Similar considerations hold for selection at the level of S. Modern Western science and engineering eventually drove out many --if by no means all -- of the useful knowledge underlying African and Asian production. To what extent this selection followed some kind of optimizing rule or was imposed by political and military means remains a matter of dispute.[56] At times techniques from one society could clash with the values and prejudices of another. Resistance to modern useful knowledge, from Copernican astronomy to the theory of evolution and modern genetics is legend, and has to be taken into account in any list of the selection criteria.

But even in historical situations in which market forces are allowed to determine the selection of the techniques to be used, there is often an indeterminacy in which techniques will actually prevail. This is particularly true in the early stages of the emergence of a new technology; frequency dependence, meaning that fitness depends not only on the intrinsic features of a specimen, but also on the number of others around, is a widespread phenomenon. In such environments, almost trivial reasons can lead to the domination of one technique over another (Arthur, 1994). Consider the example of radio: by the end of WW I three feasible technologies of transmitting continuous waves had emerged: the oscillating arc, the radio-frequency alternator,

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[56] "Modern Science" is now recognized as the one and only basis of pharmaceutical knowledge by the People's Republic of China, leading to a re-assessment of the Chinese materia medica by the criteria of modern science. Cf. Paul Unschuld, *Medicine in China: A History of Pharmaceutics.* Berkeley: University of California Press, 1986, p. 285).

and the vacuum tube perfected by De Forest which eventually became the standard technique of the industry. There is no obvious technical reason why radio technology could not have been constructed on the basis of the arc or the alternator any more than there is a good reason why the perfectable steam car produced by the Stanley company in the 1930s disappeared.

Above all, as I argued above, technology is contingent because the useful knowledge conditioning it is contingent. The Scientific Revolution as it evolved in Western Europe between 1550 and 1700 turned out to be of central importance to the evolution of modern technology, but we have no clear-cut idea how probable it was itself. Given that P(8) always depends on P(S), the likelihood of modern useful knowledge emerging needs to be discussed. By modern useful knowledge I mean much more than just the developments in mechanics, energy, chemistry, optics, biological sciences, and so on. “Modern science” was part of a larger package that arose in the post-medieval periods from Greek and medieval seeds. I have detailed these phenomena elsewhere and they are sufficiently uncontroversial to allow me to dispense with an elaborate discussion.[57] The Scientific Revolution, in addition to increasing the *size* of S, involved three important changes in its social background and attributes: (1) a scientific *method* of observation, experimentation, and testing, including a convention of *open science* in which discoveries in S were placed in the public sphere rather than kept secret, with notions of “authority,” “proof, ” and “evidence” that were very different than anything seen elsewhere; (2) a scientific *mentality* which assumed a rational, mechanistic, orderly universe with laws that are universal and understandable and which eschewed mysticism, magic and supernatural phenomena, an approach which implied the logical (but not inevitable) step of analyzing natural phenomena by mathematical tools whenever possible; and (3) a *scientific culture* that was anthropocentric and materialist, and that regarded the purpose of useful knowledge as driven by material needs and is devoid of qualms about the relentless manipulation of natural phenomena for the benefit of mankind.

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[57] Mokyr, “Knowledge, Technology.”

There was nothing inevitable about these social norms *themselves.* Indeed little is known about why and how such social norms emerge. Given that they emerged, however, the likelihood that modern S-knowledge (scientific and other) and the techniques that derived from them would occur the way they did is enhanced. Yet they were far from certain even then. These characteristics of European thinking coalesced during the Scientific Revolution and the Enlightenment, and played a substantial role in the Industrial Revolution. They conditioned the growth of S, which itself conditioned the growth of new technology. Yet we do not know how likely these norms were themselves to occur. They appeared in the West, but were they fluke or destiny?

It is fair to say that simplistic notions that predict inevitability such as "necessity is the mother of invention" are unsatisfactory and little more than empty boxes.[58] Just as there was nothing inevitable about a kangaroo or a cockroach, there was nothing inevitable about the specific forms of Dalton's atomic theory or Maxwell's electro-magnetic theory, much less about Smeaton's breastwheel and Berthollet's chlorine bleaching process, two of the crucial if less famous inventions of the Industrial Revolution. But if one believes that nineteenth century science reflected something deeper than social conventions, some theory consistent with the facts and regularities was likely to come out of the eighteenth century enlightenment.

Even conditional on the emergence of "modern western science," the precise forms that modern technology took seem less than wholly determinate. In energy, materials, communications, farming, and medical technology, to pick some areas at random, alternative scenarios can easily be imagined. Some, like semaphore telegraphs, funicular railroads, lighter than air flying machines, wind- and water power on a large

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[58] Veblen heaped scorn on the aphorism as a "fragment of uncritical rationalism" and insisted sarcastically (with considerable exaggeration) that invention was "always and everywhere" the mother of necessity. Thorsten Veblen, *The Instinct of Workmanship*. New York: Macmillan. 1914, pp. 314-17. Similarly, Carlo Cipolla states that "necessity explains nothing; the crucial question is why some groups respond in a particular way to needs or wants which in some other group remain unfulfilled." Carlo Cipolla, *Before the Industrial Revolution*, 2nd ed. New York: W.W. Norton.1980, p. 181. Lynn White points out that this fallacious aphorism can be traced to the twelfth century and cites numerous counterexamples. Lynn White, *Medieval Religion and Technology.* Berkeley CA: University of California Press.1978, p. 222.

scale, direct current, and analog computers were experimented with and then rejected because other techniques were selected. There is nothing predetermined about a Windows 98 operating system, French fries, the dashboard of a Toyota Camry, or the zipper.[59] If we could push the "rewind" button of technological history and replay the tape, we might get a quite different story.

How different depends not only on how far back the rewinding goes but also on the level of knowledge we are examining, that is to say, what facts are we conditioning the probability on. The essence of the argument made above is that if we *only* rewind the tape of 8 but keep S the same, the 8 tape would look different in detail but not in essence. It may well be that in most cases the market (or whatever other selection agency was operative) chose the "best" outcome as argued by the technological equivalent of "ultra-darwinists" such as Liebowitz and Margolis.[60] But such optimality is always conditional on what is known at that time, S_t. Had the techniques that were eventually selected not appeared on the technological menu, the technological "species" we call modern technology, would still have been *modern* [that is, of our time], but may have functioned and looked quite different.

Western vs. Oriental Technology: Chance or Fate?

We are now in a better position to return to the question of the rise of western technology. The specific forms and manifestations that western technology took were certainly contingent, but they may not have mattered. Had the West "selected" lighter-than-air instead of fixed-wing aircraft or funicular instead of locomotive-pulled railroads, its economic success and political domination would have been little changed. However, if the useful knowledge on which western techniques are based is allowed to change, and if the

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[59] The highly contingent story of the zipper is retold in Henry Petroski, *The Evolution of Useful Things.* New York: A. Alfred Knopf. (1993).

[60] S.J. Liebowitz and S.E. Margolis, "Path Dependence, Lock-in, and History" *Journal of Law, Economics, and Organization*; 11(1), April 1995, pages 205-26.

meta-rules by which intellectual resources were allocated, research topics chosen, and hypotheses formulated and tested were allowed to be different, the technological face of society would have ended up very different indeed.

Moreover, if the selection rules by which new techniques are chosen were changed, the same would have been true. The religious strictures that prevented Islam from adopting the printing press for centuries and the politics of insulation and the ban on firearms practiced by Tokugawa Japan should remind us that such selection rules may still have profound influence even when the underlying S-knowledge has become available. For the present purpose, however, I shall focus on the knowledge alone, since the issue of selection would get me into profound social and cultural issues beyond the already quite ambitious scope of this paper. Can we picture what Western technology would have looked like in the absence of certain epistemic bases?

For instance, the growth in the understanding of electricity in the eighteenth century was slow and halting. Many scientists, such as the great eighteenth century French physicist Coulomb, believed that magnetism and electricity were unrelated. But in 1819 a Danish physicist, Hans Oersted, brought a compass needle near a wire through which a current was passing. It forced the needle to point at a right angle to the current. It turned out that electricity and magnetism were related after all. From this point on, the knowledge basis started to increase quickly, and what happened subsequently may well be considered close to inevitable. Electro-magnetism, once discovered, was turned into a legitimate field of inquiry by the work of William Sturgeon, Michael Faraday and above all Joseph Henry who advised both the Englishman Wheatstone and the American Morse who built the first practical electromagnetic telegraph systems.

The early nineteenth century was a period in which “demand” for rapid communications was increasing, in part because the French revolution and the pursuant wars increased the need for rapid long-distance communications, but also because of the integration of capital markets and the development of railroads. Was the electromagnetic telegraph “inevitable”? It seems to depend crucially on whether we think that the advances in the understanding of electromagnetic phenomena, above all Oersted's discovery, was inevitable. It is inconceivable that Oersted would have been able to conduct his famous experiment without the Voltaic battery invented 20 years earlier. But we can be more precise than that. In this particular case, it is fairly straightforward to speculate that in the presence of electricity, but without Oersted, electrochemical telegraphs were a viable alternative, though they too depended on Voltaic piles.[61] Until deep into the 1840s inventors experimented with electrochemical telegraphy. It never did attain practical success, but it could have, had it not been for the greater effectiveness of electromagnetic techniques.

In the absence of Voltaic piles or similar devices relying on a growing understanding of how to generate a weak electrical current -- which would have thwarted all electrical telegraphy -- something quite different would have emerged. Chappe's semaphore system, a mechanical telegraph based on a much simpler knowledge base, was used quite widely in the first decades of the century and might conceivably have become the "norm" for long-distance communications albeit in forms modified beyond anything we can imagine.[62] It would have been less "efficient" than what actually emerged, but nobody would have known, just as we cannot know of possible techniques that were within our reach but just never occurred to anyone.

On a larger scale, then, I am arguing that from the point of view of 1400 the events in the West were

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[61] The idea of using the chemical effects of electricity as a means of long-distance communication was proposed as early as 1795 by the Catalan scientist Francisco Salvá and worked out in some detail by the Bavarian S.T. Von Soemmering in 1809.

[62] The Chappe semaphore telegraph, operating through France as well as in other parts of Western Europe, was quite successful: it could transmit under optimal conditions a bit of information from Paris to Toulon in 12 minutes in contrast with the two full days it would take a messenger on horseback. A 100-signal telegram from Paris to Bordeaux in 1820 took ninety five minutes, in 1840 half that. Given that a "signal" was picked from a code book with tens of thousands options, this was a huge amount of information. The optical telegraph at its peak covered 5000 miles and included 530 relay stations. The Chappe system was a government monopoly and did not serve as a means of transmission of private information, yet in the absence of the electrical telegraph there is no reason why it could not have played a much larger role. Another widely used visual telegraph was developed in 1795 by George Murray in England. This system rapidly caught on in England and in the United States, where a number of sites bearing the name Telegraph Hill or Signal Hill can still be found, particularly in coastal regions. Cf. Alexander J. Field "French optical telegraphy, 1793-1855: hardware, software, administration." *Technology and Culture* 35 (1994): 315-48; Daniel Headrick, *When Information Came of Age: Technologies of Knowledge in the Age of Reason and Revolution, 1700-1850.* New York: Oxford University Press, 2000.

rather improbable, even if from the point of view of 1800 they were not. Minimal rewrites would have easily have nipped the intellectual upheavals that eventually resulted in the Industrial Revolution in the bud: examples include, besides a Moslem victory at Poitiers (Lapidus, this volume), a complete Mongol conquest of Europe after Batu's defeat of the Europeans in the battle of Legnica in 1241 accompanied by a devastation of its urban enclaves; an epidemic catastrophe following the Colombian voyages on the order of what the Europeans inflicted on the destination areas; a military victory of the counter-reformation in the late sixteenth century that would have imposed Iberian standards on the intellectual pursuit of useful knowledge on the rest of the Continent. By 1688 -- and here I beg to differ from Jack Goldstone (this volume) -- the culture that created the growth of the epistemic bases of technology that led to the Industrial Revolution was in place and would have required more than a minimal re-write to dislodge.

Now suppose these intellectual developments had not happened in Western Europe. Would some other area in the world have followed a somewhat similar pattern? Would, for example, Africans have eventually invented a steam engine if left alone by Europeans? The critical question is not whether there is coal in Africa (there is) or whether Africans had the iron-working skills (they did), but whether the underlying knowledge of atmospheric pressure would *ever* have occurred in an African cultural setting. It is always difficult to test a counterfactual argument, but we are not completely in the dark. The best test case we have to compare the rise of western science and technology to is China. China developed a large and substantial body of knowledge of nature separate from the West, catalogued in great detail in the volumes put together by Needham and his collaborators. The question "if some invention had not been made in the West, would it have been made anywhere else?" may be unanswerable. But the least we can do is ask whether there is a high probability that it would have been made in China. Joseph Needham whose work on Chinese science and technology led him to view the great divergence between East and West as the central historiographical issue of our time viewed science and technology as "inseparable".[63] The two types of knowledge I have termed S and 8 are logically separate, and while they connect and interface in many areas, the intensity of interaction varies from society to society and time to time and it is perhaps this interface that merits a re-examination.

The nature and characteristics of S-knowledge as it developed in China were not "less" or "worse" that the Western experience, but its ability to serve as an epistemic base for Chinese technology clearly did not work as well.[64] Chinese technology, no matter how sophisticated and advanced upon European, remained grounded on a narrow epistemic base. Needham cites with approval the verdict of a ninth century Arab author that "the curious thing is that the Greeks are interested in theory but do not bother about practice, whereas the Chinese are very interested in practice and do not bother much about the theory".[65] As a general statement about scientific knowledge in China, this is not entirely accurate. In medicine, "theory" and practice were never separated. But, as Huff has noted, medicine was the exception.[66] In engineering, mechanics, chemistry, mining, and agriculture, the *savans* and the *fabricans* in China were as far or further apart as they ever were in Europe.[67] It is perhaps telling that while a considerable number of Chinese *techniques* in one form or another found their way to the West, there are few instances of Chinese useful knowledge (not to

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[63] Nathan Sivin,. "Science and Medicine in Imperial China – The State of the Field." *Journal of Asian Studies* Vol. 47, No. 1 (Feb 1988.), p. 47.

[64] We should not turn the story into what Sivin has called "a saga of Europe's success and everyone else's failure" (Sivin, "Why the Scientific Revolution", p. 542). Yet he himself notes a few pages (p. 537) earlier that "the privileged position of the West comes ... from a head start in the technological exploitation of nature." It is unreasonable to explain such a head start without admitting that something that Westerners learned about nature was different from what was learned in China.

[65] Joseph Needham, *Clerks and Craftsmen in China and the West*. Cambridge: Cambridge University Press. 1970, p. 39.

[66] Sivin, "Science and Medicine,"Toby Huff, *The Rise of Early Modern Science*. Cambridge: Cambridge University Press. 1993.

[67] Needham points out that the Greek distinction between theory and practice, the former suitable to a gentleman and the latter not, has a precise equivalent in the Chinese distinction between *hsüeh* and *shu*. Cf. Joseph Needham, *The Grand Titration*. Toronto: University of Toronto Press,1969, p. 142.

mention science proper) being adopted by the West.

To return to the previous example, would the Chinese have invented electrical telegraphy if the West had not? As is well known, the Chinese in the Song period had discovered magnetism and developed a floating needle that served as a compass. They had figured out some fairly advanced properties of magnetism such as magnetic declination (the error term in the compass due to the difference between the magnetic North pole and the geographical north of the planet), known as early as the ninth century A.D., and magnetic remanence (acquisition of magnetic properties due to cooling), known in the 11th century. Yet the understanding of electricity seems to have eluded them, let alone the connection between electricity and magnetism.[68] The trajectory followed by Chinese science is therefore an obvious one: given their understanding of the properties of magnetized needles, they expanded this knowledge into obvious directions (above all the compass), but they failed to make the less probable leaps made by Oersted and Henry. In the absence of Western influence, China would probably not have gone in that direction in historical times.

The issue of steampower is more complex. Pomeranz (this volume) feels that the Chinese had the "basics" for the steam engine. Knowledge of the atmosphere, and the understanding of water-condensation can surely be found, and if *all* that was required to make a steam engine was the knowledge of physics of, say, a James Watt or a John Smeaton, it is indeed likely that in the absence of the West, the Chinese would have stumbled upon something like it. But it is telling that the earliest reference to the epistemic base of steam power in China dates from the Han period and may well predate Newcomen by almost two millennia and yet nothing happened in China that we know of with certainty.[69] In the West, by contrast, models of a working

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[68] Needham, *Science and Civilization* Vol. 4, pt. 1: Physics;1962, p. 238.

[69] In his famous essay on the topic, Needham, "The Pre-natal History of the Steam Engine" published in *Clerks and Craftsmen* p. 145 tells of a document from the 2nd century BC in which a Chinese author explains that "to make a sound like thunder, put boiling water in a vessel and sink it into a well. It will make a noise that can be heard several dozen miles away," an experiment that anticipated Magdeburgian effects.

steam engine appeared half a century after Torricelli's demonstration of atmospheric pressure. Furthermore, Needham (1969, pp. 96-97) points out that the mechanical bellows described by Wang-Chên in 1313 has the structure of a reciprocating steam engine "in reverse" – but this is not really helpful: the essence of the steam engine is the conversion of heat into work, a problem cracked by Papin and Newcomen before Watt's ideas of double-acting and the famous sun-and-planets gears, which may well have had Oriental antecedents and which led of course to the transformation of Newcomen's pump to Watt's industrial source of power. Needham concedes that in this regard Europe did something that the Orient did not.[70] All the same, early steam engines were constructed on a very narrow epistemic base and in that regard it is hard to argue that the Chinese *could* not have invented it. But the likelihood is small.

One can find other examples in which Chinese society did not come up with S-knowledge that would have led them in all likelihood to techniques that would have been of use to them. Consider optics. There seems to have been a universal interest in the topic.[71] Optics is not an exactly delineated area of useful knowledge since it involves physical and physiological phenomena (the nature of light and the process by which it is received and processed by the human body). Optics was born in classical civilization, but remained essentially unapplied, the myth about Archimedes constructing concave mirrors that burned Roman ships notwithstanding. The greatest advances before Kepler's celebrated essay *Expounding the Optical Part of Astronomy* (1604), were made by Alhazen (Al-Haytam, early 11th century) who studied curved mirrors and

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[70] Needham points out that "Newcomen ... appears more original, and also at the same time more European, than [was previously realized] ... he stands out as a typical figure of that modern science and technology *which grew up in Europe only*" (*Clerks and Craftsmen,* pp. 136, 202, emphasis added).

[71] Graham and Sivin produce an interesting early beginning of Chinese Mohist studies (4th century BC) in certain areas of optics but the insights of these writing led nowhere, presumably because they were incompatible with the mainstream of Chinese natural philosophy. Cf. A.C. Graham, and Nathan Sivin, "A Systematic Approach to the Mohist Optics." In Shigeru Nakayama and Nathan Sivin, eds., *Chinese Science: Explorations of an Ancient Tradition*. Cambridge, MA: MIT Press, 1973. pp. 105-152. Whether they would have led to applied optics if Mohism had become mainstream in China is hard to know, but Graham and Sivin (p. 107) note that the optical propositions have no direct connection with technology. Other scientific sections of the Mohist Canon, however, do have such applied interest, and perhaps Mohist thinking is an example of a technological equivalent of an extinct Burgess Shale "could-have-been."

lenses and first established that light travels from the source to the eye and not vice versa. Yet from a technological point of view, the first successful application was the emergence of eyeglasses in the 1280s.[72] Without some underlying S, the probability of this technique emerging was low indeed.[73] Given that this knowledge came about, the eventual occurrence of even better spectacles (correcting for myopia in addition to presbyopia), telescopes, and microscopes were quite likely. Yet how probable was the development of useful optics? As Needham has demonstrated, the Chinese tried.[74] It is true that glass, although known in China, was not in wide use, in part the result of supply considerations (expensive fuel), and possibly in part due to lack of demand (tea was drunk in porcelain cups). But knowledge must have played the main role: not having access to the Hellenistic geometry that served not only Ptolemy and Alhazen, but also the sixteenth century Italians such as Francesco Maurolico (1494-1575) who studied the characteristics of lenses, made the development of optics difficult. The probability of a microscope being invented by someone who does not have access to geometry is very low, though it cannot be ruled out that a different kind of mathematics, not imagined by us, could have achieved the same results. Had China been the world, or had the West never had western science, optical devices similar to the ones we have would in all likelihood never have been developed.[75]

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[72] It can hardly be a coincidence that Alhazen's *Optics* was translated into Latin in 1269, about a decade and a half earlier.

[73] G.N. Cantor, "Physical Optics." In R.C. Olby et al., eds., *Companion to the History of Modern Science*. London: Routledge.1990.

[74] Thus in the *Hua Shu* (Book of Transformations) dated to the middle of the tenth century there is clear-cut reference to four types of lenses that enlarge, reduce, upright and invert. The author points out that when he looks at people he realized that there was no such thing as largeness or smallness, beauty or ugliness. (Needham, *Science and Civilization: Physics* , p. 117).

[75] It is telling that when Western applied optics arrived in China through Jesuit travelers in the seventeenth century, Chinese artisans such as Po Yü and Sun Yün-Chhiu soon constructed microscopes, searchlights, and magnifying glasses. Needham himself concedes that the view that regarded spectacles to have been a Chinese invention is a myth. Subsequent to their invention in the West, they found their way to China rather quickly. One must conclude that the Chinese were not indifferent to applied optics, but simply were unable -- given their S knowledge -- to create the techniques. Colin Ronan and Joseph Needham, *The Shorter Science and Civilization in China*, Vol. I. Cambridge: Cambridge University Press, 1978, p. 257. Needham, *Science and Civilization: Physics*, pp. 118-19.

And yet, as the steam engine example demonstrates, the presence or absence of an epistemic base does not always by itself determine the likelihood that a technique will be invented. A technique has to be "imagined" that is, it has to occur to someone, who can then map from S to produce a new technique in 8. There is nothing automatic or self-evident about this process. A lot depends on the connections between the intellectuals with the time and education to give free reign to their imagination, and the people slaving away in fields and workshops.[76] The complexity of the question is demonstrated with a later invention, anesthetics. Much like eyeglasses, the "demand" or necessity for anesthetics were hardly time- or society-specific, although the willingness and ability to tolerate and inflict pain are of course to some extent culturally determined. For hundreds of years Europeans suffered unspeakably from operations carried out without anesthesia. Discovering that a number of substances could knock a patient unconscious without long-term damage must have increased total consumer surplus (if not necessarily GDP) by a considerable amount. Yet the discovery seems to have been not just accidental but made almost in an absent minded fashion, underlining the lack of inevitability in invention as well as the absence of a need to fully understand the natural processes underlying the technique (let alone the science). Ether was first synthesized in 1540 and known as "sweet vitriol" -- why did it take three centuries till its properties were fully recognized?[77] It could have happened a

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[76] Needham points out that Chinese artisans were remarkably good at carrying out empirical procedures of which they had no scientific understanding. The real work in engineering was "always done by illiterate or semi-literate artisans and master craftsmen who could never rise across that sharp gap which separated them from the 'white collar literati'" (Needham, *Grand Titration,* p. 27). In his article in this volume, Pomeranz (this volume) points out the networks diffusing certain types of scientific knowledge clearly existed in China, but that artisans were largely outside such networks.

[77] Nitrous Oxide (laughing gas) was discovered by Joseph Priestley in 1772. No less an authority than the great Humphrey Davy suggested in 1799 that it "appears capable of destroying physical pain, it may be possibly be used during surgical operation." Ether had also been manufactured since the eighteenth century for use as a solvent, but although its anesthetic properties were known in the early nineteenth century and mentioned in an anonymous note in the *Quarterly Journal of Science and the Arts* in 1818, they were never applied to surgery until 1842. In that year Crawford Long in Jefferson, Georgia removed the diseased toe of a slave boy under anesthesia. The technique was publicized widely in 1846 by an American dentist, W.T.G. Morton, who extracted a tooth using ether. Two years earlier, Horace Wells had used laughing gas for similar purposes. The celebrated Scottish gynaecologist, James Simpson discovered at about the same time (1847) the properties of another chemical solvent, chloroform. Within a few years the idea "caught on" and surgery went through the greatest revolution ever. Ulrich Tröhler,. "Surgery (Modern)." In W.F. Bynum and Roy Porter, eds. *Companion Encyclopedia of the History of Medicine*, Vol. 2. London: Routledge.1993. Arthur W. Slater, "Fine Chemicals." In Charles Singer et al., eds., *A History of Technology* Vol. V. Oxford: Oxford University Press. 1958. Sherwin B.

century earlier, alleviating unspeakable agony for hundreds of thousands of "patients" of the surgeons of the time.

Could anesthesia have been invented in China? Unlike optics, in this case there was no need here for some breakthrough in underlying knowledge base, since little of that took place in the West either. Nobody in the mid nineteenth century had any idea *how* precisely ether, chloroform, or other substances knocked out the patient. The Chinese embarked on another route toward pain relief: instead of chemical intervention, their path led to physical means through acupuncture. Yet much of Chinese medicine was based on the use of herbal medicine and the prevalence of opium in the nineteenth century indicates that chemical intervention in sensatory bodily processes was by no means alien to them. Perhaps more plausible is the explanation that surgery itself was rare in China. [78] Conditional on that premise, perhaps the Chinese should not have been interested in anesthesia. But this argument does not seem wholly satisfactory. We need to ask what it was, if anything, in Chinese culture that made surgery unacceptable and impossible. To maintain simply that Chinese medicine was "different" from Western and therefore failed to develop surgery, anesthesia, aseptic methods, and so on strikes me as a simplification. As I noted before, there was not one but many types of Chinese medicine, just as there were different approaches to other parts of natural science. Yet none of them resulted in the adoption of surgery as a widely practice form of medicine outside cataract surgery.[79] It must be concluded, therefore, that Western itself was not "inevitable." Even given that it existed, the discovery of anesthesia was not inevitable, it did *not* occur just when the time was "ripe," and provides a powerful

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Nuland, *Doctors: The Biography of Medicine.* New York: Knopf, 1988.

[78] Paul Unschuld, *Medicine in China: A History of Ideas.* Berkeley: University of California Press.1985, pp. 150-52.

[79] The Chinese are known to have experimented with cataract surgery, influenced by Indian medicine, in the ninth and tenth centuries, yet the initiatives did not take off. When an American medical missionary, Peter Parker, opened a clinic in Canton in 1835, cataract patients flocked to him by the thousands. Chloroform anesthesia was reportedly used in China in 1848, within two years after its use in the West. Unschuld, *Medicine in China,* p. 152. S. Yung, "History of Modern Anesthesia in China." In Joseph Rupreht et al., eds., *Anaesthesia: Essays on Its History.* Berlin: Springer Verlag. 1985.

illustration of the historical contingency of techniques even when their social usefulness is unassailable and they can be made without a wide epistemic base.

The history of useful knowledge and science in China, then, is a good example of an “alternative” route that knowledge can take in different settings. It is easy and indeed tempting to attribute the differences between the growth of S in China and that in Europe entirely to different institutional settings and social environments or even the differences in geographic endowments.[80] But this ignores the path-dependence, that is, sequential nature, of S. The evolution of useful knowledge is a stochastic branching process: each step is conditioned by the state of knowledge at that time, and the direction of movement has a contingent element. By allowing for the possibility that at any point the evolution of knowledge could have gone on to a different branch than it actually did, we are implicitly allowing for a world that “knows” nature in a different manner than we do and thus exploits it in very different way. This, perhaps, is an appropriate way to think of how knowledge might have developed in China or pre-Colombian America without the West.

Even in similar institutional environments, the trajectory of useful knowledge may end up much different because a crucial ingredient was absent or present by accident, or some decision that could easily have gone one way ended up going another. To visualize the contingent nature of what actually emerged, we should carry out the following thought-experiment: think of a hypothetical society that would regard the “modern” and “progressive” West in the same way that Western historians such as Huff and Bodde have thought about Islamic and Chinese Science: admirable in some ways, but ultimately unsuccessful by the standards of another economy. Such a society might have spawned technologies we can only guess at. The only alternative is to take an arch-Whiggish view and to argue that Western science is the only “true” knowledge and that “there are objective truths out there to be discovered by the right people” the way

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[80] Huff, *Rise*, chs. 7-8. Kenneth Pomeranz, *The Great Divergence: China, Europe, and the Making of the Modern World Economy*. Princeton: Princeton University Press, 2000.

America was in 1492. This line of thought would have it that Europeans got it "right" and the Chinese (and everyone else) did not. Given that in this view there is only one objective truth, the question is then whether given enough time the Chinese or someone else would have found a road to electromagnetism, the germ theory, and quantum mechanics. But if there is more than one scientific "truth" just as there is more than one "true religion" then that likelihood must be viewed as vanishingly small.

Such are the philosophical issues involved in the counterfactual analysis of technology. What is not in dispute, as I noted in the introduction, is the effectiveness of Western technology in the battlefield, the factory, the mine, the hospital, and the research laboratory. No single element can entirely explain it by itself: an anthropocentric outlook that became the hallmark of medieval occidental Christianity, the appearance of autonomous institutions such as independent universities, the heritage of Greek and Hellenistic science, the role of medieval monks in bridging the chasm between *savans* and *fabricans*, the technology of information itself that defined the characteristics of the S set (such as the invention of moveable type printing), or the emergence of standards of open science and a pan-European "community" of scholars sharing norms and ideas. Nothing of the sort developed elsewhere, a question that has bothered the greatest historical minds of our century, Max Weber, Lynn White, Eric Jones, Joseph Needham, Nathan Sivin, and David Landes, to name just a few.

It would be as pretentious as it would be pointless to survey or add to this debate in this paper. But the evolutionary framework I proposed before may help to place one or two issues in sharper perspective. The argument I am making is *not* that for most of the time the epistemic base of technology in Europe was broader than in the Orient. As late as the middle of the seventeenth century, the differences between the epistemic bases on which technology rested in the West and China was probably not large.[81] It is rather that

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[81] Derk Bodde makes this point very strongly when he claims that by 1668, "the traditional technologies of Europe and China alike were both based more on practice than on theory and had both reached approximately the highest point possible for such technologies before the advent of modern science." Theory, however, was not really the issue. By 1700, Europeans had already vastly

the culture of useful knowledge in Europe and the institutions that supported it developed over time characteristics that allowed the epistemic bases of technology to become eventually ever wider in a host of different areas, thus creating a self-reinforcing virtuous cycle that created the huge gap between West and East in technology in a relatively short time in the late eighteenth and early nineteenth century.[82] By the end of that period, the unhappy events of the Opium Wars epitomized that gap. The question when and how the gap emerged and whether it was inevitable is thus entirely dependent on the conditioning of the probability. Conditional on the Scientific Revolution as defined above, the emergence of the steam-powered gunboats that humiliated China in 1840 was pretty inevitable. But how inevitable was the Scientific Revolution and its "mapping onto 8" (that is, interaction with technology) itself that produced the steam engines that propelled the *Nemesis*?

In reflecting on this question, it is important to realize that not only the social context of knowledge differed. The internalist view that useful knowledge in the West just developed in a different direction cannot be altogether dismissed. In the West, the selection environment of useful knowledge was more stringent than elsewhere. The physical world, in the western view was *orderly,* that is, the same causes would lead to the same effects, and one could separate between the logical and comprehensible sphere of the natural world and the theological issues of creation. These views have clear medieval roots and link back to Plato's *Timaeus*.[83]

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expanded the dimensions of S, in geography, hydraulics, optics, the manipulation of domesticated animals, graphical representation, astronomy, scientific instruments, crop rotations, and so on. Like Needham, Bodde seems too closely wedded to the linear connection between "scientific knowledge" and technical progress. His notion that "in 1687 Newton's *Principia* was published ... less than a century after, steam was beginning to turn the wheels of Britain" implies a simplistic causal connection that cannot be defended. See Derk Bodde, *Chinese Thought, Society, and Science*. Honolulu: University of Hawaii Press.1991, p. 235.

[82] Bodde (*Chinese Thought*, p. 362) provides a list of Chinese inventions such as the astronomical clock, mathematical navigation, and the seismograph which became "magnificent dead ends" (to use David Landes's term) and were not further developed. Bodde ascribes this to a Chinese lack of interest in theory. In my view, they all represent examples of singleton inventions or at least inventions with very narrow epistemic bases.

[83] The twelfth century mini-renaissance that included such writers as Peter Abelard, William of Conches, Hugh of St. Victor, Adelard of Bath, and others, might be thought of as "neo-platonist" in this regard, as it laid down the foundations of a rational and mechanistic view of the Universe that became the foundation of seventeenth century natural philosophy.

But it is hard to see why such interpretations would be inevitable.[84]

As I noted earlier, there is selection on S as well in the sense that people accept some views of the world and reject others. But the stringency of the selective pressures could vary. In a low-pressure intellectual environment many "species" of S-knowledge could coexist even if by some logical standard they were mutually inconsistent. People might believe that there are natural regularities to which there exceptions (such as magic). The selection criteria in S are culturally contingent, and it is easy to envisage a cultural climate in which the question "but is it true?" can be routinely answered by "sometimes" or "maybe" or "if God wills it."[85] Furthermore, the selection criterion "is it true" might have to compete with such criteria as "is it beautiful?" or "is it morally improving?" or "is it consistent with the wisdom of our tradition?" In the West, selecting knowledge often involved the question "does the implied technique work in practice", and a more stringent and pragmatic selection mechanism had important implications for the shape of technology.[86]

It is quite possible, then, to imagine societies in which the structure of S is such that inconsistent pieces of knowledge coexisted side by side and were accepted as the basis for techniques in the same communities at the same time.[87] The idea that two natural laws that negate each other could not both be true

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[84] Indeed, Huff (*Rise*, p. 105) notes that twelfth century Islamic writers developed philosophical views that were Platonist enough to be offensive to the Islamic religious elite but did not elaborate the rationalistic and mechanistic world view that Western Europeans built on Plato's edifice.

[85] An example is the Jain belief of *syadvada*, which can be summarized to say that "the world of appearances may or may not be real, or both may and may not be real, or may be indescribable, or may be real and indescribable, or unreal and indescribable, or in the end may be real *and* unreal *and* indescribable." Cited by Robert Kaplan, *The Nothing That Is.* Oxford: Oxford University Press. 1999, p. 45, emph.. added.

[86] Bodde (*Chinese Thought*, pp. 97-103) points for instance to "correlative thinking" as the meta-paradigm of Chinese thinking: the organic harmony of the natural world depended on that of the social world and the two were closely intertwined and one could look at one to explain the other. This meant that for instance that natural disasters could be caused by the misconduct of the Emperor. Such correlative thinking is to be found everywhere: Kepler tried to correlate the three laws of motion with the Holy Trinity and Harvey's discovery of the circulation of blood was correlated with the meteorological circulation of water. In the view of Huff (*Rise*, p. 252) who follows Bodde's lead on this "China never outgrew this way of thinking and thus did not embark on the path of causal thinking as did the West."

[87] Unschuld (*Medicine*, pp. 4-15) points out that in 3,500 years, Chinese medicine adopted demonic medicine, Buddhist medicine, religious healing, Western medicine and other foreign systems, but that these were not adopted in some kind of linear

seems to be primarily a Western one. This notion is close to the absence of a definitive concept in Chinese thinking of the idea of a rigorous demonstration or "proof," as Sivin has pointed out.[88] To be sure, even in the West the precision tools of testing one paradigm against another (with the exception of astronomy) were lacking until the nineteenth century, but once they emerged, the beliefs in phlogiston and caloric disappeared, cellular interpretations of human pathology prevailed and so on. The Copernican and the Ptolemaic views of the world or the germ- and miasma-theories of disease were recognized by both sides to be mutually inconsistent, could not coexist, so one of them had to go. But such a stringent selection environment *itself* is not preordained.[89]

Indeed, Chinese thinking about useful knowledge has had difficulty with the idea of "laws of nature" as Needham pointed out. All the same, the statement that they completely replaced Western laws of nature by "an organic world of two primary forces and five phases ... the explanation of the patterns of existence is not to be sought in a set of laws of mechanical processes , but in the structure of the organic unity of the whole" seems too strong.[90] The idea that there are regularities in nature that are predictable and exploitable is too obvious to be completely cast aside by any culture.[91] Translation becomes a key here, as the Chinese

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succession in which one system is replaced by another. Instead, often the new and the old continued to exist side by side more or less peacefully. It is interesting to note here Lynn White's remark ("Review Essay", p. 177) that in China one could be a Confucianist, a Taoist, and a Buddhist all at the same time.

[88] Cited by A.C. Graham, "China, Europe, and the Origins of Modern Science: Needham's The Grand Titration. In Shigeru Nakayama and Nathan Sivin, eds., *Chinese Science: Explorations of an Ancient Tradition*. Cambridge, MA: MIT Press, 1973. p. 62.

[89] Huff, *The Rise*, p. 105 maintains that in Islamic Society many interpretations of nature were Occasionalist, quite typical of later Islamic (Ash'arite) world-views. Such interpretations assume that natural phenomena are not necessarily subject to immutable and observable causal laws but only to the omniscient omnipotent will of God.

[90] Id., p. 251.

[91] Needham, *Grand Titration*, p. 322 cites Wang Pi, a Chinese writer from 240 AD as "We do not see Heaven command the four seasons and yet they do not swerve from their course, so we also do not see the sage ordering the people about, and yet they obey and spontaneously serve him." The thought, he adds, is extremely Chinese. Yet the regularity of the seasons can be interpreted as a "law" even if it is unclear who legislated it. Other texts confirm the recognition of such regularities (*Ch'ang*) such as the one cited in Bodde (*Chinese Thought*, pp. 332-343). Bodde, however, stresses that such texts do not invalidate Needham's belief in the absence of a Chinese equivalent of natural laws, because such views remained a minority view and could not have survived the rise of neo-

employ words like *thien fa* (laws of heaven), yet, as Needham insisted, these are laws without a lawgiver. In that sense, of course, the Chinese may have been closer to a twentieth century way of thinking about nature than to the thinking of Kepler and Newton. For the ancient Chinese, the world looked more like a "vast organism, with all parts cooperating in a mutual service which is perfect freedom."[92] Needham compares this to an endocrine system in which causality is hard to pin down and notes that modern science cannot do without it. Others have found different ways in which Western and Oriental knowledge diverged. Sivin has stressed the lack of a unity and a coherence in Chinese science caused by the absence of an overarching philosophical view of nature. In his words, China had sciences but no Science.[93]

In any event, given that useful knowledge as it emerged in China was profoundly different from the West, technological history would have taken a very different course without Western "Modern Science." There is thus no reason to believe that a world without the West would have come upon the internal combustion engine, the microprocessor, or stereotaxic surgery. The Chinese might have, however, quite likely stumbled on smallpox vaccination, semaphore telegraph, hot air ballooning, Bessemer steel, aspirin or other inventions requiring narrow epistemic bases. But the mutually reinforcing interaction between science and industry that created modern metallurgy, chemical engineering, biological technology, and such would simply never have taken place.

This is not to say that without the Rise of the West, the Orient would forever have been as inward looking and stagnant as it was in 1850. They might have once again have built a grand fleet and explored the world. A Japanese-Korean-Chinese collaborative effort, under the right set of circumstances, might have created a dynamic not unlike the North Atlantic semi-competitive research program that produced the second

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Confucian thinking from the eleventh century on.

[92] Ronan and Needham, *The Shorter* Vol. I, p. 167.

[93] Sivin, "Why the Scientific", p. 533.

Industrial Revolution. Material wealth and even a degree of technological sophistication can be and were created with narrow-based techniques. At some point, however, the gains from further technological experimentation would have started to level off without the mutual reinforcement of S-knowledge and 8-knowledge.

And yet, at the end of the day it is hard to know precisely whether Oriental science, had it been left alone long enough by the West, would not have developed into something so radically different from what we are used to that we cannot even imagine it. That takes us back to fig. 1: an evolutionary view of the world suggests that there are possible states of the world that are not imagined, but that *might* have occurred given the opportunity. The problem is that such opportunities, too, depend on historical contingency. This kind of area is precisely what the region M denotes. We can, by definition, have no idea what M may contain nor how large it may be. Just as a lot of indigenous flora and fauna in isolated demes have their evolutionary path cut short or altered irreversibly by a catastrophic event or the invasion of a fitter species, thus technological evolution can be affected by the invasion of a "fitter technology." There is no way of knowing whether Pre-Columbian Peru or Maori New Zealand would ever have developed forms of technology that would astound us the way Marco Polo was astounded by China and the way New Guinea natives were astounded by Western technology. We can be pretty sure, however, that unless they somehow managed, against all odds, to produce an S set similar to that produced by Galileo, Lavoisier, or Maxwell, the technology in use in these areas would have looked very different from what it looks like now.

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