Technological Innovation as an Evolutionary Process

Edited by JOHN ZIMAN

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Evolutionary models for technological change

JOHN ZIMAN

1.1 The biological analogies

Go to a technology museum and look at the bicycles. Then go to a museum of archaeology and look at the prehistoric stone axes. Finally, go to a natural history museum and look at the fossil horses. In each case, you will see a sequence, ordered in time, of changing but somewhat similar objects. The fossils, we know, are sampled from the history of a family of biological organisms. They are similar because they are related by reproductive descent. But here – and quite generally throughout this book – when we say that they have *evolved* we mean more than that they have 'developed gradually'.[1] We are indicating that this development has occurred through genetic variation and natural selection, sometimes, in outwardly static circumstances, apparently spontaneously, sometimes as an adaptive response to a changing external environment. Can technological innovation be explained in similar terms? Do *all* cultural entities 'evolve' in this sense – that is, change over time by essentially the same mechanism?

These museum displays, and the similarities between them, are, of course, highly contrived.[2] But the basic analogy between biological and cultural evolution has often been remarked.[3] From the middle of the nineteenth century onwards, it was noted more or less independently by such eminent scholars as William Whewell, Karl Marx, Thomas Henry Huxley, Ernst Mach, William James and Georg Simmel. The basic idea has been extended by later authors such as Jean Piaget, Konrad Lorenz, Donald Campbell, Karl Popper and Jacques Monod. Sometimes it is presented as just one aspect of a general principle of 'Evolutionary Epistemology', which interprets the whole story of human social, intellectual and material development as the continuation of organic evolution by other means.[4] But it is a simple idea that makes obvious sense in its own right – for example, in accounting for the immense variety of artefacts that are invented and put on the market, and for the superior utility of the few that eventually survive.[5]

What is more, it is an idea that can easily be developed in considerable detail. Try it out in conversation around the coffee table. Most people nowadays know enough about how Darwin explained 'the origin of species' to apply the same reasoning to 'the origin of inventions'. They regularly refer to technological concepts in quasi-biological terms – 'fitness', 'survival', 'niche', 'hybrid', 'genealogy', etc. – as if the analogy needed no further explanation. This usage is so convenient that we shall employ it throughout wherever it is not misleading. Indeed, the theme of this book is perfectly exemplified by the usefulness of the technical language of evolutionary biology for summing up succinctly a variety of cultural phenomena.

First of all: it is very easy to point to *structural* analogies between certain biological processes and the processes involved in technological innovation. One can immediately think of mechanisms whereby material artefacts – indeed, also, less tangible cultural entities, such as scientific theories, social customs, laws, commercial firms, etc. – undergo *variation* by *mutation* or *recombination* of characteristic *traits*. Many different variants are put on the market (or published, or practised, or adjudicated, or invested in, etc. as the case may be). There they are subjected to severe *selection*, by customers and other users (or competing groups, courts of appeal, banks, and so on). The entities that *survive* are *replicated*, *diffuse* through the population and become the predominant type.

Further thought reminds us that *mutualistic* relationships are very common, as between pens and inks, or between bombers and radar systems. Indeed, technical innovations in an industry such as car manufacture are so interrelated that one might describe it as a whole *ecological system* of *coevolving* artefacts. As the selective environment changes, so do such systems evolve and *adapt* to it. On the other hand, isolated subpopulations – *demes* – may separate and evolve independently in different directions for long periods before recombining. And so on.

What is more, the history of technology provides numerous episodes that are remarkably similar to well-known biological phenomena. Some of these *phenomenological analogies* will be discussed in later chapters of this book. Overall they make an impressive list. In my own limited reading I have come across suggested technological analogues of what an evolutionary theorist would term *diversification*, *speciation*, *convergence*, *stasis*, *evolutionary drift*, *satisficing fitness*, *developmental lock*, *vestiges*, *niche competition*, *punctuated equilibrium*, *emergence*, *extinctions*, *coevolutionary stable strategies*, *arms races*, *ecological interdependence*, *increasing complexity*, *self-organization*, *unpredictability*, *path dependence*, *irreversibility* and *'progress'*. Admittedly, some of these suggested similarities are very questionable, so that it would take us too far afield to cite, decode and try to justify them in detail. Indeed, the whole biological analogy is often dismissed as naive. But the mere fact that such a list can be compiled at all shows just how many quite specialized 'evolutionary' characteristics are apparently common to both technological and biological systems.

1.2 The technological 'disanalogies'

The directness and diversity of these analogies strongly suggest the possibility of transforming the notion of 'technological evolution' from an evocative *metaphor* into a well-formed *model*. But before trying to set up such a model, we must look at the flip side of the comparison. Unfortunately, as many students of the subject have pointed out, there are many 'disanalogies' to take into account. Technological systems are not like biological systems in a number of important ways.

The most obvious difference is that novel artefacts are not generated randomly: they are almost always the products of conscious *design*. In the language of neo-Darwinism,[6] they are not 'Weismannian': the variations that are presented for selection are not produced by a mechanism that is entirely blind to their ultimate fate. Inventors learn by experience and experiment, and visualize their creations before they make them. Their inventions thus acquire characteristics which are deliberately handed on to the next generation. Technological innovation thus has 'Lamarckian' features, which are normally considered to be forbidden in biology.

Another major difference is that there is no strict technological equivalent of a biomolecular *gene*. To sustain the overall analogy, it is convenient at times to talk about technological systems in terms of 'memes'[7] – elementary concepts that endure over long periods, replicate themselves and shape the actual artefacts. But this terminology is abstract and metaphorical. 'Memes' are not operationally equivalent to the indivisible entities hypothesized by Mendel and made flesh by Crick and Watson. The characteristic features of an artefact cannot be analysed uniquely into precisely defined design elements that endure unchanged for long periods. Thus, all bicycles have wheels, but these are so varied in design and construction that it is not very useful to regard them as manifestations of a 'wheel meme' that persists from type to type.

'Meme' language is instructive, of course, in emphasizing the heritability of technological traits, as distinct from the physical survival of the artefacts that exhibit these traits. Biological theorists make much of the relationship between the *phenotypes* that are actually subjected to selection, and the *genotypes* that encode them. This is much simpler and more precise than the relationship between artefacts and their 'memotypes'. The design of a novel artefact is often analysed and revised many times before any engineering work begins. Technological memes can be transmitted, stored, revived, varied and selected independently of the actual artefacts to which they might apply. It would be possible, for example, to construct a workable modern 'penny-farthing' bicycle solely on the basis of an old photograph or patent specification.

But here again, there are serious 'disanalogies'. The genome of a biological organism is a 'recipe' for its development from conception, rather than a 'blueprint' of its adult form. In technological evolution, 'memes' from distant lineages often recombine, and 'multiple parentage' is the norm. No biological organism is like, say, a computer chip, which combines basic ideas, techniques and materials from a variety of distinct fields of chemistry, physics, mathematics and engineering. Does the differentiation of organisms into separate *species*, which Charles Darwin made central to evolutionary theory, truly apply to inventions? The 'cladogram' of a technological artefact usually looks more like a neural net than a family tree![8]

1.3 Is 'evolution' compatible with 'design'?

At first sight, then, the evolutionary metaphor for technological innovation is very appealing. In many respects, both the underlying mechanisms and the broad patterns of technological change are quite reminiscent of those found in biological evolution. But the idea of turning these structural and phenomenological analogies into a realistic model soon meets obstacles. Indeed, these obstacles have seemed so daunting that only the most daring scholars of the subject – notably the late Donald Campbell – have tried to surmount them. The viability of the project embodied in this book is thus seriously in question!

To proceed further, it is essential to understand what we are up against. The first major obstacle has deeper roots than the Lamarckian heresy. 'Design' is central to modern technology.[9] How can that be reconciled with 'evolution', which both Darwin and Lamarck explained as a process through which complex adaptive systems emerge *in the absence* of design? We may well agree that technological change is driven by variation and selection – but these are clearly not 'blind' or 'natural'. This work is being done largely by conscious human effort, without apparently needing guidance from any 'hidden hand', whether of Nature, the market, or God.

An evolutionary model incorporating intentional factors, such as memory and mental imagery, thus seems self-contradictory. Should we abandon the project altogether, in favour of some other theoretical paradigm, such as 'self-organization', or 'social constructivism'? To avoid this, advocates of 'universal Darwinism'[10] rightly point out that human cognition is the product of natural selection, and operates on selectionist principles.[11] They thus maintain the 'blindness' of the whole process by locating all the action in lower-level neural events whose causes might as well be considered random for all that we can find out about them. Alternatively, the effects of design are assimilated notionally into the selection stage of the cycle, where already-achieved wisdom is used, as in computer problem-solving, to reduce the search space.[12] But these are reductionist strategies that complicate the model far beyond any hope of practical application. Throughout this book, therefore, we shall accept these intentional factors in the way that we ordinarily understand them – for example, as reported to us in everyday psychological terms by 'creative' persons engaged in inventive activities.[13]

But does the 'random variation' that is such a fundamental element of an evolutionary mechanism really have to be as 'blind' as, say, the mutation or recombination of molecules of DNA in sexual reproduction? Remember Darwin's insight that it is *populations* that evolve, not individual organisms. All that may be required is that there should be a stochastic element in what is actually produced, chosen and put to the test of use.

In practice, design processes are always imperfect and indeterminate. As we all know, the 'best-laid plans' of inventors, engineers, research managers, market analysts, company directors, etc. 'gang aft agley'. What is more, there is usually so much uncertainty and disagreement on so many significant points that a wide range of artefacts is made available for selection. Again, the criteria by which technological innovations are selected are not universally agreed, so that artefacts with similar purposes may be designed to very different specifications and chosen for very different reasons. In other words, this apparently deep-rooted obstacle has little substance. There is usually enough diversity and *relatively* blind variation in a population of technological entities to sustain an evolutionary process.

1.4 Artefacts as cultural constructs

'Design' denotes more than rational construction. It indicates *purpose*. A technological artefact is defined in terms of its practical use. Unless novel specimens are made completely mindlessly – and that would not be true even of the stereotypical stone axe – their variant features are bound to be correlated with their intended role in the lives of their makers. After all, this is what distinguishes an 'artefact' from a 'useful object', such as a pebble picked up for throwing.

A technology is not really separable from the *culture* in which it is embedded. Material artefacts encode, embody, convey or transmit whole systems of immaterial ideas and behavioural patterns. It is only for brevity that we talk about them as if they were specimens in a museum, identified only by a name and acquisition date, as if unaware of the invisible cultural aura that gives each object its meaning.

Indeed, the concept of 'technology' – 'the application of practical sciences to industry or commerce'[14] – is not restricted to material objects. It also includes a whole variety of systematic technical procedures, such as farming routines or medical therapies, where the material instruments are not the centre of attention. The spectrum of *social constructs* stretches without a break from concrete objects such as stone axes, bicycles and aspirin pills, to the most abstract entities such as commercial contracts, legal precedents and economic theories.

In other words, a comprehensive model of technological innovation would have to cover almost every aspect of *cultural* change. In this book, we focus, for simplicity, on the evolution of tangible cultural objects such as swords, cathedrals, turbojets and pharmaceutical products. But the social context in which and for which they are produced is not merely a passive environment to which they must adapt. Many intangible features of the surrounding culture – for example, military techniques and commercial practices – change over time, hand in hand with the changes in the artefacts to which they are connected.

Thus, if technological entities (in the narrow sense) are deemed to 'evolve', then this interpretation must surely extend to the social entities with which they interact. In default of an alternative theory of a socio-cultural change, we have to include them in our evolutionary model along with their technological counterparts. This book is necessarily much concerned with the complications arising from this widening of the basic metaphor.

1.5 Institutions, roles and behaviour

The above argument can be turned on its head. One could well say that we are interested primarily in the evolution of *cultural* entities in general,[15] and choose to study material artefacts because they have the useful property of being concrete, relatively stable physical objects. They are amongst the few socially meaningful entities that can be preserved unchanged for centuries and are not dissipated by close scrutiny. Their evolutionary trajectories ought to be much easier to investigate and understand than those of less tangible cultural entities, such as languages, rituals, organizations or ideologies. Thus, the study of technological innovation, seemingly so marginal to the humanistic endeavour, could eventually lead right into its centre.

In other words, our starting point might have been evolutionary interpretations of cultural change as such, rather than the analogies between technological and biological evolution. Indeed, there is an extensive, if rather incoherent literature on this subject,[16] which will be referred to in detail at various points in this book. But much of this literature is not really relevant to our theme, since it mainly derives its conceptual framework from *sociobiology*. That is to say, it is concerned primarily with the evolutionary interaction between the biological traits of human beings – in particular, hereditable traits such as sexual preferences, linguistic capabilities, affective responses, etc. – and their social behaviour.[17] This *coevolutionary* process was obviously fundamental to the emergence of modern humans as social beings.

But the biological engine of sociobiology seems to have run out of steam many tens of thousands of years ago.[18] On the other hand, cultural evolution has continued at an ever-increasing pace. Indeed, quite enough technological innovation has taken place since then to provide ample material for our study. We may confidently assume, therefore, that all the 'inventions' that we are concerned with in this book originated amongst people who were physically, intellectually and emotionally 'just like us'.

What is more, we can discard the 'methodological individualism' intrinsic to sociobiology and evolutionary psychology. That is, instead of trying to reduce social action to patterns of individual *behaviour*, we can analyse it in terms of the *institutions* that shape it and give it meaning. Here, of course, we are adopting a much disputed sociological stance. But it does allow us to talk intelligibly about the evolution of organizations, social roles, cultural practices, languages, symbols, concepts, etc. without being committed to any particular opinion about whether such entities are 'really real'.[19]

Indeed, as we noted incidentally above, 'Darwinian' processes of variation and selection can be observed at work amongst commercial firms, social customs, laws, scientific theories, etc. For example, *evolutionary economics*[20] focusses on industrial firms, treating them as social institutions driven by market forces to adapt to changing technological regimes. One of the obvious features of technological innovation in an advanced industrial society is that it involves the coevolution of marketable artefacts, scientific concepts, research practices and commercial organizations. The transistor, for example, was a novel engineering device conceived theoretically by solid-state physicists working in the research and development laboratory of a telephone company. Each of these elements not only contributed to the process of innovation, but was itself changed by its participation.

But here again, by starting with entities at the material end of the spectrum of cultural entities, we do not run head-on into the fog of indefinability surrounding more general theories of 'cultural Darwinism'. Even the most systematic of these theories[21] have encountered very serious conceptual difficulties in trying to identify the units of variation and selection in, say, the abstract world of scientific theories. The application of evolutionary theory to narrowly 'technological' change promises to avoid some of these difficulties, or at least to meet them in a different order, with different weights, and sometimes in simpler forms.

1.6 Selectionism versus instructionism

We can now see that a realistic evolutionary model of technological change must be more complicated than its biological counterpart. It has to incorporate 'design' as well as 'selection', and must extend into the domains of social institutions and abstract ideas. Biologists often complain about the misconceptions of non-biologists about the nature of organic evolution, and about their ignorance of the diversity of its mechanisms.[22] But the processes at work in technological innovation are extremely heterogeneous, and change radically from era to era. As a result, the analogies and disanalogies between biology and technology look different according to what we choose to place at each end of the comparison.

There is a temptation to leap over these messy complications by proposing ever more abstract versions of Darwinism. But a watered-down model designed to meet all such objections would be weaker even than the basic metaphor. The standard neo-Darwinian account of biological evolution has a logical coherence and proven explanatory power which is hard to match. The challenge is to retain and exploit these virtues in the cultural domain.

In particular, what are we to make of the striking phenomenological similarities of biological and technological change? Perhaps these phenomena are not really sensitive to the structural details of the system. Perhaps they are common to all systems that evolve by mechanisms that include stages of partially random variation, selection and replication.[23]

This line of argument is confirmed by the results of computer simulations on very simple models. The burgeoning literature on artificial life, genetic algorithms, cellular automata, etc.[24] contains instances of almost all the phenomena common to technological and biological evolution. For example, some forms of artificial life clearly exhibit ‘punctuated equilibrium’: they evolve almost imperceptibly for long periods, with sudden episodes of radical change.

Thus, instead of lumping technology and biology together into the same species, we should perhaps treat them as distinct members of a larger genus of *complex systems*.[25] Rather than insisting that our ideas about evolutionary processes should conform to strictly ‘Darwinian’, or ‘neo-Darwinian’ principles, we should be exploring the properties of a more general *selectionist* paradigm.[26] We could then give up such Procrustean exercises as trying to make industrial firms look just like organisms, and design concepts just like genes, and concentrate on the actual structural relations between the entities that make up each type of system. In other words, our evolutionary model of technological innovation need not be quasi-biological, just as our evolutionary model of the biological world need not be quasi-cultural, even though they have many general features in common

1.7 Understanding innovation

That, in outline, is the realm of thought that opens up behind the evolutionary metaphor for technological innovation. What do we hope to gain by exploring it further?

In the first place, improved understanding of cultural change is not irrelevant to evolutionary biology. Evolutionists tend to take biology as the standard model, as if all evolutionary processes had to conform to its peculiarities. The exploration of an alternative system throws into relief those features that are specific to biology, such as nearly permanent genes and sexual reproduction, and suggests limits to their evolutionary functions. Would a ‘Lamarckian’ factor necessarily alter the nature of a ‘Darwinian’ mechanism? Might it not just improve the efficiency of the search for a higher peak in fitness space? Could it perhaps facilitate self-organization and damp out some of the random fluctuations as the system – life itself – approaches the edge of chaos?

Less hypothetically, technological change is one of the most striking features of our present-day civilization. And yet, in spite of much research effort, it still escapes elucidation. It would overwhelm this book to go through all the different theories, models and metaphors that have been proposed to explain how it occurs. A ‘selectionist’ approach to this puzzling problem area promises to show more clearly the relative roles of apparently contrary factors, such as ‘creativity’ and ‘design’. Should one think of material artefacts or conceptual ‘memes’ as the entities that evolve? Historians, ethnographers and prehistorians of technology might then consider whether there has been a progressive move away from selection towards design in the invention or improvement of artefacts. We shall probably never know how much systematic thinking went into the production and selection of stone axes; it is still unclear how much random trial and error will really be needed in the creation of the next generation of 'designer pharmaceuticals'.

Indeed, technological innovation is of such enormous social importance that it is worth pursuing such questions further into the interstices of scientific, industrial and commercial life. What is the actual relationship between 'selection' and 'design' in the research and development divisions of industrial firms? Does this relationship differ from firm to firm, or from industry to industry – and if so, why? Is the overall process speeded up by more feedback (and feed forward) between the various stages, or does each system evolve at its own characteristic rate? What are the real selection criteria in various types of market? An evolutionary perspective should yield new insights into such practical matters.

This exploration of a plausible proposition thus starts with many more questions than it can ever expect to answer. There is evidently plenty of conceptual and empirical space into which it can expand and evolve. That, surely, is a blessed state for any worth-while intellectual enquiry!