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Evolutionary Theory of Technological Change: Discussion of Missing Points and Promising Approaches

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I. Introductory thoughts

There are concerns that in order to exploit the powerful new capabilities provided by the Information Technology Era, it is necessary to advance Future-oriented Technology Analysis (FTA) of both product and process. Among these new capabilities, the FTA Methods Working Group (2004) has recently identified three main converging areas of development: complex networks, simulation modeling of complex adaptive systems (CAS) and the search of vast databases. Such convergence has rejuvenated the growth of FTA methods and practice, much in accordance with the perspective envisioned in Linstone (1999), following his optimistic view of a strong, confident technology-driven scenario, which would bring a renewed impetus toward new methods in technological forecasting (figure 1). The picture suggests that the chaotic phase transition might be behind us and that the new impetus is all around, which we can also infer from the integration of the field discussed in the above referred paper (TFA Methods Working Group, 2004) (not to mention the recently adopted umbrella concept of FTA!).

Focusing on new methods related to the new capabilities, we must borrow the discussion of methods and tools that have explosively grown in recent years in the fields of biosciences, bioinformatics and evolution. Among the needs for FTA envisioned by the FTA Methods Working Group, we find a questioning about the validity of the analogy between technological evolution and biological evolution (TFA Methods Working Group, 2004): “Can artificial technological worlds be created by simulation modeling analogous to biological ones?” This question is hardly a new one, and we can even trace at least a three-decade long debate on this issue. What makes the difference today, are exactly those powerful new capabilities provided by the Information Technology Era and the manifold convergence of information and molecular technologies that are contributing enormously to new insights in simulation methods and evolutionary programming. In the previously cited 30-year anniversary issue of Technological Forecasting and Social Change, Bowonder *et al* (1999); briefly reviewed this topic by mainly focusing on some of the lessons learned from evolutionary theory as it anticipates changes in evolutionary trajectories, and proposed a research agenda for future research. But these authors have not considered, in detail, the new capabilities and have not identified the possible problems and obstacles that must be overcome to transform evolutionary approaches into useful forecasting tools.

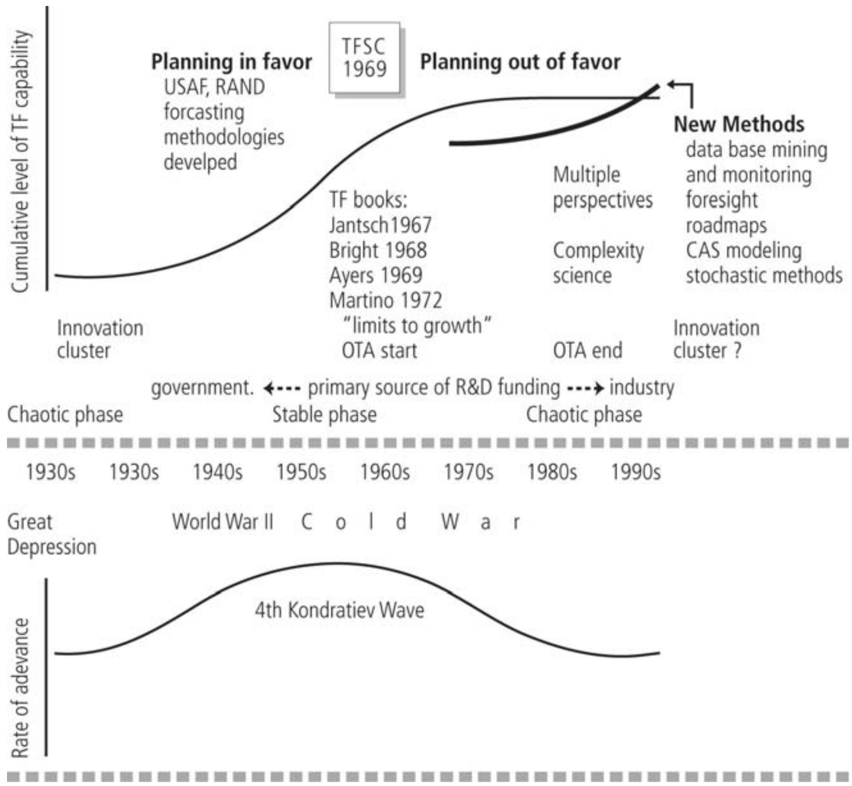

Figure 1 – Technological forecasting in perspective presented by Linstone in the 30-year anniversary issue of Technological Forecasting and Social Change (1999).

The present paper intends to present the state-of-the-art on this debate and to address some important considerations necessary to answer the above question. The sense one gets from the published literature on this theme is that the effort to-date has been primarily centered on the striking similarities between biological evolution and technological evolution and is mostly based on verbal theorizing. It seems that a synthesis of biology and technology remains beyond reach, with some people even doubting whether it can ever be achieved. In the following lines we intend to point out and briefly discuss some quite important aspects that have been overlooked and misinterpreted in this exciting debate.

II. Some missing pieces…

It is usually said that some biological evolution-related concepts like mutation, selection, adaptation, life cycle, survival of the fittest, etc, are useful metaphors in the realm of economics, business and technology assessment. But few people realize that the inverse is also a common usage: as systems increase in complexity, it becomes necessary to draw upon social experiences to provide the necessary analogies (Brown, 2003). This is the case in cellular and molecular biology, where we find, for instance, a cell seen as a factory, with complex relationships and functions such as signaling, energy budget, transport, and quality control. Peter Corning (2003) has pointed out that complexity – in nature and human societies alike – has been shaped by the "payoffs" arising from various forms of synergy. Cooperation, "payoffs", networks, agents, and some other conceptual figures, which first originated in the reasoning about the social realm, have become over the last years the most common figures permeating social and natural sciences as well.

The metaphorical language provides the means for understanding and talking about abstract ideas and entities that are not directly observable, in terms of concepts grounded in very basic physical and social perceptions. The more complex and intangible the system, the more useful is the resort to metaphors. That is evidently the case in the *theory of evolution* itself: we evoke metaphors in both ways, from the biological to the social and also the other way around, from the social to the biological. And it has continued since Darwin himself, and has made Darwinism such a controversial and long-lived scientific discipline, which is still open to further developments and applications.

Theorizing about the evolutionary (Darwinian) aspects of technological change is then not merely a question of using metaphors and making analogies, as we find in the literature on the theme. There are some further and subtle aspects to consider that, in my point of view, are still not well taken into account in the variety of discussions found in the literature. These aspects may make up some of the missing pieces that will complete the puzzle of a firmly based *evolutionary theory of technological change* (ETTC for short), and are listed as points in the paragraphs below in a quasi-logical sequence. Needless to say, these points are strongly inter-related and difficult to comment on without some overlapping of ideas:

❶ - Biology, or perhaps more generally, biosciences, is not merely a good source of metaphors, but historically it was, it still is and I strongly believe that it will endure as the most powerful means to capture and to describe the ecosystem (which includes the aggregate human behavior) and will be the seed and/or the substract for further development of useful forecasting tools in the technological realm. This is a historical fact to which follows the need to acknowledge the law-like aspect underlying all growth phenomena in the living (social as well) realm, mainly related to the mechanism of information transmission and the increase in a system's complexity.

❷ - The development of a working ETTC depends upon the *correct understanding* of three difficult-to-define concepts, usually taken as granted by popular common sense: technique, technology and (technological) innovation. An evolutionary approach within the framework of 'anthropology of technique' is a necessary step to grasp adequately these concepts.

❸ - Universal Darwinism is still not well understood and this has delayed the entrenching of evolutionary economics as a powerful complementary tool to other current economic models. Mainstream economics still has strong objections to the application of pure Darwinian principles in the working of agents in the socioeconomic realm. This barrier must be overcome to construct a working ETTC.

❹ - It does not make sense to develop an ETTC starting from the analogies and/or contrasts found between biological and techno-cultural evolution, or in other words, between the evolution of organisms and artifacts. It urges the acceptance of the general principle of 'Evolutionary Epistemology', which interprets the whole history of human social, intellectual and material development as the continuation of biological evolution by other means. It still fails to recognize that there are some other fundamental laws (or driving forces) underlying *evolution* as a whole and these must be added to the already acknowledged general rules of blind variation plus selective retention.

❺ - Finally it should be added that, in comparison with the relatively vast literature found in verbal theories of techno-cultural evolution, the amount of practical work using simulation methods is still a small/tiny one. Although recognizing that the fields of evolutionary computation and artificial life are still emerging sciences, some important modeling attempts were undertaken during the last decades and I think that some of the above mentioned points are hindering the development of working computational algorithms to simulate technological evolution.

It is impossible to accomplish the full discussion of all these points in a short working paper. I hope that the following text commenting briefly on each of these points should serve as a basis for establishing an effort toward an international research agenda on the subject.

III. …to complete the puzzle

To point 1: more than a useful metaphor

One of the most powerful technological forecasting tools, the logistic equation, has its origin in the biological realm and has won the status of a natural law of technology diffusion due to its considerable success as an empirically descriptive and heuristic device that captures the essentially changing nature of technologies, products, markets and industries.

Viewed on the most general level, living systems, from cells to societies, exhibit common properties, with some attending intrinsic *fundamental invariants*. Recognition of this fact in the last decades is leading firmly to a new scientific paradigm, a complex bio-socio-economics, with the convergence of different fields of science toward what may be the clue to understanding the modus operandi of *evolution* per se – the development of evolutionary algorithms for many different problem-solving and/or theoretical applications. The fields of evolutionary computation and artificial life have reached a stage of some maturity and we are witnessing today an intense debate on universal Darwinism as a broad theoretical framework for the analysis of the evolution of all open, complex systems, including socio-economic systems (see point 3 ahead).

Evolutionary arguments in economics, as in biology, originally took purely verbal forms, and it was only with considerable delay that more mathematical (algorithmically based) arguments and models were advanced. The mathematical tools, that began to be employed in economics (as well as in technological forecasting) in the 1970s, had been developed by mathematical biologists in the 1920s and 1930s and were widely known. The widespread availability of computers (and of computer literacy) has undoubtedly contributed to the rapid diffusion of the usage of such mathematical tools, but this delay in uptake was caused by a common obstacle: the slow recognition of the appropriateness of evolutionary arguments at all.

Formalization of evolutionary thinking in biology in algorithmic terms began when R.A. Fisher (1930) published his work *The Genetical Theory of Natural Selection*, introducing what are now called *replicator equations* to capture Darwin's notion of the *survival of the fittest*. A very important aspect of Fisher's approach when introducing for the first time the *fitness function* was that of natural selection acting at the population level, which closely followed Darwin's original idea. By the same epoch, and not necessarily motivated by evolutionary concepts, the bio-mathematicians Vito Volterra and Alfred Lotka popularized a set of differential equations to describe the growth of population levels, most commonly know as predator-prey (or multi-competition) equations. It is important to note that recently Hofbauer and Sigmund (1990) demonstrated that Volterra-Lotka and replicator equations are equivalent.

Yet the American biologist and demographer Raymond Pearl (1925) in his seminal book *The Biology of Population Growth* called attention to the fact that the growth of populations is essentially a phenomenon of biological nature, that is, a phenomenon involving natural processes of reproduction and diffusion. Comparing different growth processes, like the growth of organisms (measured by the body mass), the growth of a population of yeast cells (in an appropriate nutritive solution), the growth of a population of Drosophila melanogaster, or even the growth of human populations; Pearl observed that all growth processes could be adequately described by the logistic or Verhulst equation (which as we well know is a particular case of the Volterra-Lotka equations, when a single population is competing for limited resources in a confined niche). The question at that time was *why can a single universal algorithm (the logistic equation) describe so different growth processes*? In the first case (the growth of a body mass), one is measuring indirectly the cumulative growth of a population of cells, not competing for resources and whose limit is dictated by genetic inheritance. Yeast cells are unicellular organisms competing for resources and multiplying themselves by cellular division; while Drosophila are complex organisms doted with devices for digestion and sexual reproduction. In both cases there is no kind of genetic inheritance controlling the ceiling of the growth process. Whereas, human beings are not only much more complex organisms, but also have a complex interconnection of motivations for living and reproduction.

It was not until the 1970s that the Volterra-Lotka equations found numerous applications in the world of business and technology assessment; such as describing the competition among firms or innovations, or simply among products struggling for a bigger market share. It is well known the case of the pioneering work of Fisher and Pry (1971); who demonstrated the validity of the normalized logistic equation in accounting for technological substitution processes or for the diffusion of basic technological innovations. Cesare Marchetti (1980) and Theodore Modis (1992) contributed further to this development calling attention to the closed relationship between the growth and diffusion of innovations and pure learning processes (for instance, the growth curve of a child's vocabulary achievement, which also follows a pure logistic trajectory). Moreover, Modis (1992) has demonstrated the complete equivalence between the learning curves (exponential decaying) used in the economy of scale (learning by doing) and the logistic (S-shaped) curves. More recently Devezas and Corredine (2001) proposed a generalized diffusion-learning model to explain the succession of long waves in the techno-economic world, whose basic mechanism of recurrence is controlled by two kinds of biological determinants (constraints – generational and cognitive) that impose the rhythm of collective human behavior.

All this is to say that the use of biological approaches in analyzing the evolution of technology or the unfolding of economic phenomena (in small or worldwide scale) is not a matter of simple metaphorical comparisons. We have witnessed a natural evolutionary process of the human understanding of the socioeconomic realm that was forced to follow (we may say in a fractal fashion) the same path, which will inevitably lead to the recognition that cultural evolution is the continuation of biological evolution by other means. It is absolutely clear that *learning* has a definitive role in the technological or cultural evolution (we will turn to this aspect when discussing points 4 and 5), but it is not sufficient to explain the ubiquity of the logistic curve in the living world.

The question remains: what is the common denominator underlying the growth phenomena of populations of multiplying cells, Drosophila, humans, and innovations? From my point of view the common denominator lies in the basic mechanism of *information transmission* (and also of information growth, which also begets complexity growth) a point that has not been suitably accounted for in the efforts to find a universal evolutionary algorithm.

To point 2: a necessary anthropology of technique

In 1904 Hugo De Vries, the eminent Dutch botanist that rediscovered Mendel's laws and developed the mutation theory of evolution, wrote: "Natural selection may explain the survival of the fittest, but it can not explain the arrival of the fittest". This statement, written a century ago, epitomizes one of the greatest mysteries of evolution still challenging scientists – *the emergence of novelty*. All of the extraordinary organizational forms and behavioral strategies that we witness in nature or society have arisen through the process of inheritance with diversification and selection. The formal treatment of evolutionary dynamics is presently cast in terms of the changing frequencies of some fixed entities: genes, linkage groups, individuals, social groups, and even memes (in the cultural realm). Yet it is the arising of these robust and resilient structures, in other words, *the emergence of innovations*, that is of profound interest, both theoretically and for the applications that this understanding would facilitate.

Here we are also dealing with one of the most controversial points in all previous attempts to compare biological with technological evolution, that can be subsumed under the following questions – are *innovations* (or novelties) in the biological, cultural, and technological realm of the same nature? And if the answer is positive, what is the underlying set of rules driving their emergence and continuous unfolding? There are many reasons to think that the answer is indeed positive, some of them will be considered shortly in this paper, as well as some of the candidate rules (point 4 ahead) driving the phenomenon and still absent from much of this discussion.

To begin with it should be pointed out that the notion of *innovation* belongs itself to that collection of fuzzy concepts, that along with some other (not necessarily related) hard-to-define terms like for instance *globalization* and *complexity*, are the currency of contemporary economic and scientific debates. Everyone knows intuitively what they are, but nobody can satisfactorily offer a short (and at the same time broad) definition of each of them. But unlike *globalization* and *complexity*, that are more or less restricted to economics, business or politics (as in the case of globalization) or restricted to more scientific discussions (the case of complexity), *innovation* is by far the more transversal of them, reaching probably all possible human spheres of action. On the Internet, a Google search yields the following results (July 2005) – 17.1 million hits for *globalization*, 41.2 million for *complexity*, and 127 million for *innovation*! Furthermore, another winner in this modern competition is *evolution* with more than 85 million hits, and shows how evolutionary thinking permeates modern human thought!

Most authors agree that it is impossible to define innovation in a context-free manner, and this difficulty is not necessarily made easier if we restrict our analysis to technological innovation (our present context). I want to advance the following arguments favoring an evolutionary approach to define innovation and then answer in the positive the above question about the same nature of novelties in the biological, cultural and technological realm:

① Novelty in any sphere of the living world (that includes social systems) seems to arise 'out of nowhere', in spite of strong constraints that stabilize extant structures;

② In biological systems an innovation can be achieved without necessarily changing the genetic underpinnings of a feature, but by shifting the context and timing of their expression within the developmental sequence of an organism. This suggests that a feature's integrity depends on a systemwide network of interactions involving other features. The same statement is true in a technological context if we substitute the words genetic underpinnings with *building blocks* (following John Holland's (1998) original proposition of model building and emergence) and organism with *artifact*.

③ Evolution of organisms is the conjunction of two facts: the selective amplification of genotypes based on the differential reproductive success conveyed by their phenotypes through chance events at the level of genotypes. Again the same statement can be used in the technological realm by substituting words: genotypes with any sequence of *building blocks*, differential reproductive success with *differential adoption in a market* and phenotype with *technical expression*.

④ My final argument favoring an evolutionary definition of innovation regards the aspect mentioned above of how strongly evolutionary thinking permeates modern human worldview (accepting or not accepting the idea of an *intelligent designer*).

My proposed definition is then simply:

Innovation is the emergence of a new adaptive design.

This definition has sufficiently broad meaning and can be easily applied in the domain of cultural traits or technical artifacts. But, as commented on above, when we focus the evolutionary analysis on technological innovations we are not necessarily simplifying the field of discussion, but instead we are adding some difficulties about which disagreement abounds in the published literature. In spite of the fact that nearly everyone agrees that to explain technological advances we must look beyond the artifacts themselves, we have some crucial troubles when talking about fundamental ideas behind them. Some of these fundamentals are:

1 – what should be the suitable *unity of analysis* in technological evolution? Or in other words, what then actually evolves? Artifacts themselves, the technical knowledge to make them or some combination of these? Or the interface of artifacts and ideas in technological practices?

2 – how does *heritability* occur in technological systems? That is, how do technological units (whatever they may be) carry their *information* forward through time?

3 – are technological innovations indeed *teleological or Lamarckian* in nature or not? Looking at the history of inventions and basic innovations we can find some evident cases of intended and/or planned novelties as well as apparently common cases of a wide range of dramatic early random experimentation with radically different designs, which branch further and then settle down into a few dominant lineages.

In a very recent book edited by John Ziman (2003) we have different authors theorizing about these questions, but unfortunately we can not see much progress when we compare these contributions with texts published in the 1980's, as for instance the very often cited books of Nelson and Winter (1982) and Basalla (1988). There is still little in the way of formal theorizing and model building, and we can say that a lot of work remains to be done to make evolution a viable strategy and school of thought in the study of technology. In my view what is missing is a bridge linking evolutionary concepts in biology to technological progress, but a bridge leading to a level higher up than the plain mapping of every element of technological evolution onto a precise correspondence in the biological counterpart.

Such a bridge could be offered by a better-developed anthropology of technique, in the way paved by the German philosopher of technology, Hans Sachsse (1978), almost three decades ago. Sachsse (whose work was mostly published in German and has remained in a kind of limbo, probably obfuscated by the 'evolutionary epistemology' developed by Karl Popper, with which it shares many common points) considered that *humans through their technical handle continued natures work*, or in other words, *we have helped nature in its evolution*. In the points below I try to resume some important aspects that were never consistently considered in the attempts to build a model of an ETTC:

1 – *Technique* precedes *technology*, not only in human history, but also under a pure evolutionary point of view. Technique (or *routine*, which is often the same thing) did not need a brain or mind to come into existence in the course of biological evolution: very primitive life forms have developed skilled techniques of gathering food, of attracting partners for mating, of camouflage to avoid predators, and of capturing prey. Some primitive underwater beings are very successful killing machines. In a single

coral reef we can witness a wonderful ebullience of rough life forms performing a huge range of trickeries to survive and reproduce.

2 – In the course of biological evolution the *technique* came to life as a form of *searching for a bypass* (or *shortcut*) to reach a goal, because it is easier to pursue this goal through the bypass. In my view this is a clear manifestation of the *principle of the least action* in practice, which has worked as the underlying driving force for better and better search procedures, amplified by the development of *learning* capabilities (we will turn to this point ahead).

3 – Following this reasoning we can state then that *humans, when dealing with technique, do in a conscious way what nature always did unconsciously*. In other words we can say that human technical skills are the continuation of this natural search for bypasses by intelligent means.

4 – Another important conclusion is that the existence of learning capabilities and the further development of brain and mind came into life because nature owns the basic structure (then a fundamental law) of arriving at shortcuts to reach easily the goals immediately ahead.

5 – *Technology is a recent human achievement* that flourished conceptually in the 18th century, when technique was seen as no more than skilled handwork, but has turned as the object of systematic human knowledge and a new 'Weltanschaung' (at that time purely mechanistic). This terminus was proposed first in 1777 by the German economist Johannes Beckman (in his opus *Einleitung zur Technologie oder zur Kenntnis der Handwerke, Fabriken und Manufakturen*) as *science from the technique*, or the *Lehre* as men perform something (technical) at their best.

With this short collection of ideas I wish to suggest that a firmly conceptually based anthropology of technique is still lacking in the current attempts of model building and formal theorizing of an ETTC. At this stage it is worth pointing out that I agree with Joel Mokyr (2003) that the unit of analysis that makes sense for the study of technological evolution is the *technique*.

To point 3: demotion and rise of evolutionary concepts in economics

It is a well known fact that the social sciences after experiencing an initial impulse from evolutionary concepts at the turn of 19th to 20th century have historically insisted on ignoring Darwinian ideas. Economics, in some ways the most ambitious of the social sciences, progressively abandoned biology and adopted physics as its natural science model. Social scientists, and particularly economists, have never correctly realized that Darwin in his second and long-ranging intellectual torpedo (1871 –*The Descent of Men and Selection in Relation to Sex*) has devised a theory that was more applicable to cultural traits than to genetics (which was foreign to his thinking). Darwin himself was confused by the mechanism of inheritance, and, by always imagining that organic inheritance included the feature of inheritance of acquired variation and by liberally using the concept of inherited habits, he gave birth to the most controversial scientific debacle that lasted for over a century.

But during the last two decades we have seen a growing interest in evolutionary ideas among economists. New professional associations focusing on these ideas have been founded and for more than fifteen years there has been the *Journal for Evolutionary Economics* (Springer) devoted particularly to this topic. This upswing in evolutionary economics was in great part due to the renewed interest in the discussion of long waves in economics over the last two decades, which opened the way to the revival of Joseph Schumpeter's ideas of an evolutionary global economy driven by the clustering of basic innovations and creative destruction of older ones during economic depressions (for a review on this topic see Devezas and Corredine, 2001).

However the basic ideas underlying evolutionary economics are still a matter for considerable controversy. Among the main objections we can find the following examples:

- some modern approaches from complex systems theory, like self-organization, are alternatives to biological analogies or Darwinism;
- artificial selection is an alternative to natural selection in the socio-economic sphere;
- Darwinism excludes human intentionality.

We have no space in this paper to discuss in depth these objections, but as demonstrated in a recent article published by Geoffrey Hodgson (2002) in the *Journal for Evolutionary Economics*, it is relatively easy to show that all these objections are ungrounded. In fact Darwinism includes a broad theoretical framework for the evolution of all open, complex systems, including socio-economic systems, and also involves a basic philosophical commitment to detailed, cumulative, and causal explanations, as envisioned by Richard Dawkins (1983) in his *Universal Darwinism*. Hodgson (2002) stated that Darwinism provides a compelling ontology and it is a universal theory in which specific theories must be nested. However, Darwinism does not provide a complete explanation of socio-economic phenomena, something more is required. As I already pointed out before, the social cannot be reduced to the biological, a point of view also stressed by Hodgson (2002): *Darwinism may be universal, but economics should not be abandoned to biology*. There are the missing pieces I have mentioned in this paper (see further discussion in the next section) and the necessary bridge to the anthropology of technique discussed previously.

To point 4: technological evolution as the continuation of biological evolution by other means (or more than blind variation plus selective retention)

Karl Popper's (1972) view of scientific progress as a cumulative selection process resembling Darwin's natural selection threw new light on the evolutionary concept of human cultural development. He proposed *the natural selection of hypotheses*, asserting that our knowledge consists, at every moment, of those hypotheses that have shown their fitness by surviving so far in their struggle for existence, a competitive struggle that eliminates those hypotheses that are unfit. This hypothesis has paved the main road followed by modern thinkers in cultural evolution, beginning with Donald Campbell (1960) (who coined the term *Evolutionary Epistemology* to characterize Popper's epistemology) and leading to some conceptual breakthroughs like Richard Dawkin's *memes* in the 1970's and more recently Daniel Dennet's (1995) *Darwin's Dangerous*

Idea (the idea that all the fruits of evolution, not only organisms, can be explained as the product of a mindless and mechanical algorithmic process).

Campbell defended a *universal evolutionary or selection theory*, claiming ultimately that *all innovative design* is produced by one or another variation-plus-selection-plus-transmission process, and proposed the acronym BV (blind variation) + SR (selective retention) to designate the process. The most important arguments introduced by Campbell in this discussion can be summarized as:

- unlike biological evolution, characterized by direct trial and error adaptation processes, knowledge processes evolve through *vicarious forces*, that is, inherited-acquired (by learning) psychological forces that act as surrogates for natural selection because they arose themselves by natural selection;
- in the case of genetic evolution, the most important evolutionary forces, processes that are capable of changing gene frequencies and causing evolution, are mutation, genetic drift, gene flow, and natural selection, making unvarnished organic evolution a purely random variation and selective retention process. Technological evolution (and cultural evolution as a whole) must be subject to more or less *analogs* of these four forces, but is also subject to several kinds of vicarious forces. People are not only selected willy-nilly by natural selection, they also make conscious and unconscious choices as they learn from themselves and from others.

In essence, Campbell forcefully reintroduced Darwinian ideas to social sciences (economics as well), after a lapse of almost a half century after the initial impetus commented on in point 1. Basically he suggested that Darwinism contained a general theory of the evolution of all complex systems, and made the point that the appropriate analogy for social evolution is not biotic evolution, but the more general process of evolution of complex systems ‘for which organic evolution is but one instance’. However, the above arguments, obvious as they may seem, are still a matter of intense controversy – people insist in just looking for the analogs/similarities/examples of the above mentioned four forces or simply reject Darwinism because it can not account for the human intentionality – a very wrong and biased attitude.

In my view Campbell’s concept of vicarious forces provides a suitable mechanism to ensure that cultural evolution does favor the fitness of our genes, or in other words, the basic process of *Gene-Culture Coevolution*, which is the most appropriate approach to develop a firmly based ETTC.

When discussing the previous points I have already pointed out some features that have not been yet accounted for in the body of existing work on technological evolution. To finalize the present discussion in point 4, I would like to add some further aspects that have also not yet been considered:

- if technique had not favored an organism’s pool of genes or genes transmission it would not have evolved into technology;
- if technology had not favored a human pool of genes or human genes transmission it would not have continually evolved toward more and more complex technological systems;

- human's massive capacity for culture (and technology) may be seen as a very strong capacity to adapt to very quick spatial and temporal variations, observed on Earth since the Pleistocene;
- the coevolutionary complexity of managing two inheritance systems (the vertical, genetic, and the horizontal+vertical, cultural) does not imply necessarily the highest degree of perfection, for we must consider the many cultural pathologies observed in human society. It serves almost exclusively to human's (genetically inherited) quick capacity of response to rapidly changing environments or as Richerson and Boyd (2001) so brilliantly stated "Humans are built for speed not for comfort'', a point of view also shared by Marchetti (1987).
- *technological evolution can not be thought as an independent evolutionary process*, but it is part (the most energetic one) of a broad co-evolutionary set of processes, manifest as a cascade of multilevel, nested, and self-similar Darwinian-like processes, which on the whole constitutes the world system, as recently empirically and mathematically demonstrated by Devezas and Modelski (2003);
- this set of processes is fundamentally *innovation driven* (each in its own scale), exhibits power-law behavior and is poised in the critical boundary between order and chaos (poised in the sub-critical-supracritical phase transition boundary), what allows for the necessary flexibility required to take part in the selection process at the several levels of the evolutionary game.

To point 5: some promising approaches

As already mentioned there is a relatively vast literature on verbal theories of technological and cultural evolution, but there is relatively little work proposing formal models and using simulation methods in this field. Among the reasons for the lack of practical-oriented works we have referred to:

- the persistent opposition of mainstream economics to Darwinian concepts as applied to socio-economic systems, mainly caused by misinformation and non-acquaintance with the basic assumptions of universal Darwinism;
- the insistence of trying to map every element of technological evolution onto a precise correspondent in the biological counterpart;
- the absence of a suitable basis of reasoning that could be offered by the 'Anthropology of Technique';
- the still missing pieces (some of them are principles of a very general nature, commented on in the previous sections, which I will return to in the conclusions) to complete the puzzle;
- the fact that the fields of evolutionary computation and artificial life, in spite of some maturity as sources of efficient heuristic tools to solve complex problems, are still emerging sciences.

There are two possible approaches to simulating technological and/or socio-economic systems. The systems dynamics approach, widely used in technological forecasting since the 1950s, is top-down in character (so called because it views the system from above, as a whole). It is usually applied to human feedback systems and their dynamics (behavior over time) is defined via the change of their organization (or state) as described by the system's differential equations. Such top-down analyses are very suitable for describing system's regularities and identifying dominant feedback loops, or in other words, for forecasting agents' aggregate behavior.

The other approach forms the new sub-field of artificial life (AL, for short) that uses so-called soft computing models of complex adaptive systems (CAS) that encompasses several methods of simulation and it is best characterized as a bottom-up approach. Its origin stems from the 1970s with the emergence of gaming simulation. Theoretically and methodologically, this approach makes possible the construction of models from the level of processes that are immediately and empirically observable, namely the local interactions of single units (agents) governed by local rules.

Although a consistent ETTC still does not exist and a formal (algorithmically based) model allowing the simulation of technological evolution has not yet been developed, there are some attempts following this approach that deserve to be mentioned here. It is worth pointing out, however, that although this methodology is being used by a few research groups worldwide, it is impossible to do justice to all efforts of all groups found in the literature, as well as to discuss in this paper the details and the results attained by these groups.

The formal mathematical models developed in the past two decades and most often used are (mentioning only some important publications for each approach):

- *NK technology landscapes*, initially proposed by Stuart Kauffman (1995) and further pursued by other researchers of the Santa Fe Institute, like José Lobo, J Miller and Walter Fontana (2004).
- *Complex network analysis*. This is a new and emergent scientific branch that is finding increasing applications in a wide range of fields, from physical sciences, to life sciences and to social sciences. The system's most important characteristic unraveled by this method is the existence of scale-free networks, which seem to be ubiquitous in nature and subjacent to all CAS. Scale-free networks pervade technology: the Internet, power-grids and transportation systems are but a few examples. For a review on this field I suggest the reading of two recent review articles (Frommer and Pundor, 2003; Barabasi and Bonabeau, 2003) and regarding its application to technological systems see the work of Ricard Solé *et al*. (2002), also conducted in close collaboration with other researchers at the Santa Fe Institute.
- *Cellular automata*, initially developed for gaming simulation and widely publicized by one of its most famous developers, Stephen Wolfram (2002), has been applied to the evolutionary simulation of the innovation diffusion process by a group at Hebrew University led by Jacob Goldenberg and Sorin Salomon (Goldenberg and Efroni, 2001; Goldenberg *et al*, 2004).
- *Percolation models*. A numerical simulation method for the search of complex technology spaces based on percolation theory, using also some general principles of cellular automata and NK landscapes. It has been used for instance by some researchers of the Maastricht evolutionary school of economics (MERIT), as Gerald Silverberg and Bart Verspagen (2005) for the study of the distribution of innovations;
- *Genetic Algorithms (GA's).* Also widely known as evolutionary algorithms, or evolutionary computation, were invented by John Holland (1998) in the 1960s and were developed by Holland and his students at the University of Michigan in the 1970s. In technology and science, GA's have been used as adaptive algorithms for

solving practical problems and as computational models of natural evolutionary systems, and are considered today a relatively mature computational tool for solving complex engineering problems, for which the term *Modern* Heuristics (Michalewicz and Vogel, 2002) was coined. Regarding their use in the simulation of technological evolution it has been used by one of Holland's students, David Goldberg (2000), for instance, for studying the connection between the two basic processes of innovation, continual improvement and discontinuous change. Goldberg proposed the use of the algorithms *selection* + *mutation* and *selection* + *recombination* as expressing the basic mechanisms of *continual improvement* and *innovation* respectively.

In the present stage of our knowledge no one can be sure about which method is best suited for purposes of simulating technological evolution and/or for developing useful tools for technological forecasting. Altogether the application of these methods within the limits imposed by their own characteristics has helped researchers in unraveling some until now hidden properties of technological systems. My personal opinion is that, among the above-mentioned methods, cellular automata is the poorest for more sophisticated simulations due to the simplicity of its basic assumptions and limitations that must be imposed by the rules governing interactions between agents. Undoubtedly the strongest potential belongs to genetic algorithms, or more generally speaking to genetic programming (a refinement of GA's developed in 1987 by John Koza, 1992), as we can infer from very recent results (*Evolving Inventions*) announced by John Koza *et al* (2003) from Stanford University. They claim to have reproduced *in silico* 15 previously patented inventions in the field of electronics (6 of them patented after January 2000) and have applied for a patent for a genetically evolved general-purpose controller that is superior to mathematically derived controllers commonly used in industry.

IV. Conclusions

The new science of *Digital Darwinism* based on further improvements of genetic algorithms and genetic programming, may be considered the most promising candidate for establishing the knowledge basis of a working Evolutionary Theory of Technological Change, as well as for developing useful tools for TFA. What remains to be done, besides the improvements in the computational methods, is to incorporate in the simulations some of the general evolutionary principles that were outlined in the present paper, and that until now were not suitably considered in previous modeling attempts. A short summary is presented below of these missing fundamental considerations:

- *the common denominator to all growth and diffusion phenomena in the living world* is the *transmission of information,* whose continuing evolutionary process lead to increasingly complex systems;
- *cultural evolution* (and technological evolution as well) is the *continuation of biological evolution by other means*;
- *technique is the most suitable basic unity of analysis* and must be viewed as the *enduring search for bypasses* (shortcuts) *obeying the general physical principle of the least action*;
- *technology* must be viewed as the *further improvement of this process by intelligent means* (which also allows for intentionality), possessing both mechanisms of variation – simply random (Darwinian) and intentional;

- *human technology* is part of a biologically *co-evolved massive capacity for culture*, *managing two inheritance systems*, vertical (twofold in scope, genetic and Lamarckian) and horizontal (pure Lamarckian in scope), that serves fundamentally for human's quick capacity to adapt;
- *technological evolution* is not an independent evolutionary process, but it is the fastest and most energetic among a *broad innovation-driven and co-evolutionary set of processes*, composing the whole of the *world system*.

It is important to point out that the considerations listed above are original in scope, but the Darwinian logic used shares common points with Marchetti's (1998) vision exposed in a short and elegant piece published some years ago. Marchetti's preselector mechanism is a typical example of the use of the minimum principle in nature, which ubiquitously uses the fastest and not the shortest path.

References

Barabasi, A.-L., and Bonabeau, E., 2003, Scale-Free Networks, *Scientific American*, May 2003, 50-59.

Baslalla, G., 1988, *The Evolution of Technology*, Cambridge University Press, Cambridge, UK.

Bowonder, B. *et al*., 1999, Predicting the Future: Lessons from Evolutionary Theory, *Technological Forecasting & Social Change*, **62**, 51-62.

Brown, T.L., 2003, *Making Truth: The Roles of Metaphors in Science*, University of Illinois Press, Champaign, IL, USA.

Campbell, D.T., 1960, Blind Variation and Selective Retention in Creative Thought as in other Knowledge Processes, *Psychological Review*, **67**, 380-400.

Corning, P., 2003, *Nature's Magic: Synergy in Evolution and the Fate of Humankind*, Cambridge University Press, Cambridge, UK.

Dawkins, R., 1983, Universal Darwinism, in D.S. Bendall (ed), *Evolution from Molecules to Men*, pp. 403-425, Cambridge University Press, Cambridge, UK.

Dennett, D., 1995, *Darwin's Dangerous Idea – Evolution and the Meaning of Life*, Simon & Schuster, New York, NY, USA.

Devezas, T., and Corredine, J., 2001, The Biological Determinants of Long-Wave Behavior in Socioeconomic Growth and Development, *Technological Forecasting & Social Change*, **68**, 1-57.

Devezas, T., and Modelski, 2003, G., Power Law Behavior and World System Evolution, *Technological Forecasting & Social Change*, **70**, 819-859.

De Vries, H., 1904, *Species and Varieties, Their Varieties by Mutations*, Kegan Paul, Trench, Trubner & Co., London, UK.

Fisher, R.A., 1930, *The Genetical Theory of Natural Selection*, Clarendon Press, Oxford, UK.

Fisher, J., and Pry, R., 1971, A Simple Substitution Model of Technological Change, *Technological Forecasting & Social Change*, **3**, 75-88.

Frommer, I., and Pundor, G., 2003, Small Worlds: a Review of Recent Books, *Networks*, **4**(13):174-180.

Goldberg, D., 2000, The Design of Innovations: Lessons from the Genetics, Lessons fro the Real World, *Technological Forecasting & Social Change*, **64**, 7-12.

Goldenberg, J., and Efroni, S., 2001, Using Cellular Automata Modeling of The Emergence of Innovations, *Technological Forecasting & Social Change*, **68**, 293-308.

Goldenberg, J., *et al*., 2004, Inevitably Reborn: the Reawakening of Extinct Innovations, *Technological Forecasting & Social Change*, **71**, 881-896.

Hodgson, G.M., 2002, Darwinism in Economics: from Analogy to Ontology, *Journal of Evolutionary Economics*, **12**, 259-281.

Holland, J., 1998, Emergence: From Chaos to Order, Perseus Books, Cambridge, MA, USA.

Kauffman, S., 1995, At Home in the Universe, Oxford University Press, New York, NY, USA.

Koza, J., 1992, Genetic Programming: On the Programming of Computers by Means of Natural Selection, MIT Press, Boston, MA, USA.

Koza, J. *et al*., 2003, Evolving Inventions, *Scientific American*, February 2003, 52-59.

Linstone, H.A., 1999, TF&SC: 1969-1999, *Technological Forecasting & Social Change*, **62,** 1-8.

Lobo, J., Miller, J.H., and Fontana, W., 2004, Neutrality in Technological Landscapes, SFI-Working Paper, Santa Fe, New Mexico, USA.

Marchetti, C., 1980, Society as a Learning System: Discovery, Invention and Innovation Cycles Revisited, *Technological Forecasting & Social Change*, **18**, 257-282.

Marchetti, C., 1987, Infrastructures for Movement, *Technological Forecasting & Social Change*, **32**, 373-393.

Marchetti, C., 1998, Notes on the Limits to Knowledge Explored with Darwinian Logic, *Complexity*, **3**, 22-35.

Michalewicz, Z., and Vogel, D.B., 2002, *How to Solve it: Modern Heuristics*, Springer, Berlin, Germany.

Modis, T., 1992, Predictions: *Society's Telltale Signature Reveals the Past and Forecasts the Future*, Simon & Scuster, New York, NY, USA.

Mokyr, J., 2003, Evolutionary Phenomena in Technological Change, in Ziman, J. (ed.), *Technological Innovation as an Evolutionary Process*, Cambridge University Press, Cambridge, UK.

Nelson, R.R., and Winter, S.G., 1982, *An Evolutionary Theory of Economic Change*, Beknap of Harvard University Press, Boston, MA, USA.

Pearl, R., 1925, *The Biology of Population Growth*, Alfred A. Knopf, New York, NY, USA.

Popper, K., 1972, Objective Knowledge: an Evolutionary Approach, Oxford University Press, Oxford, UK.

Richerson, P.J., and Boyd, R., 2001, Built for Speed, Not for Comfort, *History and Philosophy of the Life Sciences*, **23**, 425-465.

Sachsse, H., 1978, *Anthropologie der Technik*, Vieweg, Braunschweig, Germany.

Sigmund, A., and J. Hofbauer, J., 1990, *Dynamical Systems and the Theory of Evolution*, Cambridge University Press, Cambridge, UK.

Silverberg, G., and Verspagen, B., 2005, A Percolation Model of Innovation in Complex Technology Spaces, *Journal of Economic Dynamics and Control*, **29**, 225-244.

Solé, R.V. *et al*., 2002, Selection, Tinkering, and Emergence in Complex Networks, SFI-Working Paper 02-07-029, Santa Fe, New Mexico, USA.

Strumsky, D., and Lobo, L., 2003, If it isn't broken, don't fix it, Extremal Search on a Technology Landscape, SFI-Working Paper 03-02-003, Santa Fe, New Mexico, USA.

TFA Methods Working Group, 2004, Technology Futures Analysis: Toward Integration of the Fields and New Methods, *Technological Forecasting & Social Change*, **71**, 287-303.

Wolfram, S., 2002, A New Kind of Science, Wolfram Media, Inc., Champaign, IL, USA.

Ziman, J. (ed.), 2003, *Technological Innovation as an Evolutionary Process*, Cambridge University Press, Cambridge, UK.