Don't Predict the Future – Direct It!

Comments on the intellectual history, the logical and applicative visibility, and the underlying assumptions of Directed Evolution (DE)

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The best way to predict the future is to invent it. ***Alan Kay***[1]

It is obvious that there are patterns of cultural change – evolution in the neutral sense – and any theory of cultural change worth more than a moment's consideration will have to be Darwinian in the minimal sense of being consistent with the theory of evolution by natural selection of Homo sapiens. ***Daniel Dennett***[2]

The future is here. It's just not widely distributed yet. ***William Gibson***[3]

It is the magician's wand, by means of which he may summon into life whatever form and mould he pleases. ***Charles Darwin commenting on the power of artificial selection***[4]

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[1] Alan Kay is one of the inventors of the Smalltalk programming language and one of the originators of the idea of Object Oriented Programming. He is the conceiver of the laptop computer and the architect of the modern windowing GUI.

[2] Daniel C. Dennett is a Professor of Philosophy and Director of the Center for Cognitive Studies at Tufts University. He is the author of several books, including *Consciousness Explained* (1991), *Darwin's Dangerous Idea* (1995), *Kinds of Minds* (1996). This quote is taken from his forward to *Darwinzing Culture* (Aunger, 2000) p. ix.

[3] In the early 1980s William Gibson wrote *Neuromancer*, coining the term "cyberspace" to describe computer-generated virtual realities long before we saw the similarities with today's Internet.

[4] Here Darwin is explaining the power of artificial selection and its potential for the directed evolution of biological systems (domestication and commercially-oriented breeding) in his *Origin of Species*, 1859: 68.

Abstract

This article introduces an applied Theory of Evolution of Artificial Systems, called Directed Evolution (DE). The theory is grounded in fifty years of research on Inventive Engineering known as TRIZ which started in the former Soviet Union by G. Altshuller and continues today. The theory has generated a set of Patterns and Lines of Evolution which represent a compilation of trends that document strong, historically-recurring tendencies in the development of man-made systems in general and technological systems in particular. Directed Evolution is the systematic applied-oriented process for "predicting" future generations of a system by inventing them along these evolutionary patterns. The current article introduces the theory, reflects on its basic underlying logic, and provides a broad historical context and intellectual justification for such an effort. It shows that the quest of DE theory and practice falls well within the boundaries of past pursuits to identify evolutionary patterns of complex systems and to use these patterns to control and manipulate possible futures of artificial systems.

Keywords: Technological foresight; Directed evolution - DE; Innovation management; Technological forecasting; Evolutionary patters; Cultural Evolution; TRIZ; Future studies; Design.

Introduction: Towards proactive "guided innovation" with Directed Evolution

This article introduces an applied theory of evolution of artificial systems called Directed Evolution (DE). Its main message is that there are certain principles and evolutionary patterns that seem to guide and govern the growth and development of culturally-produced systems, especially technological systems. It has taken more than five decades of research in a domain of knowledge called TRIZ (a Russian acronym for the Theory of Inventive Problem Solving) to come to the realization that technological systems tend to evolve not randomly, but according to repetitive (and therefore, potentially, predictable) evolutionary patterns or trends that have heretofore been unpredictable. TRIZ was first developed in 1946 by Genrich Altshuller, a 20-year-old inventor who had studied the intellectual property contained in some 200,000 patents, from which he identified about

40,000 as representing the most effective solutions in almost every domain. Altshuller was convinced that the process of design and invention could be defined by more than creativity and luck, and studied patents to discern patterns in the processes that applicants had used to come up with the designs they were trying to patent. From that, the Theory of Inventive Problem Solving was born (Altshuller, 1984, 1997). Although originating in the former Soviet Union, most of the theoretical and applied TRIZ research today is conducted in the United States by the Ideation Research Group. The products of their theoretical and applied work are designated as I-TRIZ (the Ideation/TRIZ methodology) to mark their advancements and contributions to so-called classical TRIZ. The Ideation Research Group is currently the center of gravity in contemporary cutting-edge TRIZ research, and one may think of it as the Xerox PARC (the legendary research and innovation center of Xerox) of TRIZ. In this sense, and as will be shown below, Directed Evolution is the independent, free-market American offspring of the original Russian TRIZ.

The term "Directed Evolution" was introduced in 1994 by the I-TRIZ people to refer to the complex of works related to the management and the control of the evolution of technological systems. Specifically, Directed Evolution is an advanced rendering of a classic Altshullerian TRIZ procedure called *TRIZ Technological Forecasting*. The important differences between these two approaches will be discussed later in this paper; for now, we will only say that Directed Evolution's main focus is on finding ways to control and "direct" (via R&D) the evolution of technological systems and to use these efforts to generate and secure a high-value portfolio of Intellectual Property (IP) for those who use DE to develop the system. After five decades of research, unknown for the most part (yet) to the scientific and business communities, we now know of at least a dozen general evolutionary patterns and approximately 400 more detailed "lines" of technological development associated with these patterns.

Here is a brief outline of the basic logic of Directed Evolution. The notion of *Patterns of Evolution* used in the application of DE represents a compilation of trends that document strong, historically-recurring tendencies in the development of man-made systems. A pattern usually contains a set of *Lines of Evolution* that describes in greater detail typical sequences of the stages (positions on a line) that a system follows in the process of its natural evolution. For example, studies of the history of technology and of thousands of patents reveal a certain pattern/line/trend called *Element Universalization*, which states that in the process of evolution, technological systems tend to become more universal and multi-purpose, in order to provide convenience and to satisfy multiple needs. This observed evolutionary pattern is accompanied by increased dynamism, because greater universality requires greater flexibility and "adjustability." Once the position of a given system on a universal line has been determined (that is, its position in reference to a "specialized-universal" continuum), the possibility of transitioning to the next position(s) can be assessed. In some situations it may be obvious how this transition should be made and the evolution of given product or service (system) may be strategically "directed." The existence of these universal patterns raises the possibility of making statistically-reliable predictions of potential evolutionary scenarios for technological systems; knowledge of such patterns may also be used to "force" the evolution of given products and services (and even whole industries) into a consciously-selected, pre-determined future evolutionary scenario. Directed Evolution's main focus is on finding ways to control and "direct" (via R&D) the evolution of technological systems and to use these efforts to generate and secure a high-value portfolio of Intellectual Property (IP) for those who use DE to develop the system. In business terms the implication of these statements to companies is clear: awareness of these patterns and mastery of the methodologies that exploit them means a major competitive edge in dimensions such as market share, time-to-market and, above all, the ability to secure a strong IP portfolio before one's competitors. By 2007, dozens of TRIZ Forecasting and DE projects have been completed in the chemical, automotive, consumer product, software development and other industries.

When first encountered and realized, the power and the potential implications of Directed Evolution are so striking that they are sometimes hard to conceive. This ambitious, and in this author's view, successful, effort raises a degree of healthy skepticism expressed in "this is too good to be true" or equivalent reactions. This article attempts to deal with these kinds of reactions and, in a way, is as much about the viability and theoretical possibility of such an application-oriented intellectual pursuit to provide fruitful (i.e., applied) findings as it is about Directed Evolution and its associated findings. Nevertheless, it will attempt to prove the value of DE from the "outside-in" – that is – it will not rely on DE's achievements (i.e., success stories of effective application) to make the case but rather will follow logical arguments and cite historical examples from the history of science and technology to show that the effort and approach of Directed Evolution is a worthy effort. Clearly, this is somewhat paradoxical since the theory of Directed Evolution, at least in general terms, has already been phased and tested in demanding business settings. Yet, rather than providing examples and success stories from industry, we try here to show that a theory of Directed Evolution is a possible, logical and potentially fruitful effort in the context of the history of scientific pursuits for general principles of both cultural and technological systems. This is what sets this account of Directed Evolution apart from other papers on the subject, and we hope that this contribution will add a new angle to the topic.

Accordingly, the current paper will focus on the basic underlying logic of DE and will attempt to provide a broad context and intellectual justification for such an effort. Since Directed Evolution is, in the final analysis, an attempt to abstract the seemingly endless complexity of artificial-technical systems into a small number of governing laws and principles, we start by making the case for reductionism as a research quest and as an organizing principle in scientific research. We then continue to discuss Charles Darwin's theories of artificial and natural selection and attempt to evaluate the logical and intellectual relations between the two and Directed Evolution. We will then try to show that, in a way, Darwin's theory of artificial selection (that is, selective breeding of plants and animals that is *directed* towards a pre-determined *domesticated product* such as a desired variety of carrot or a Thoroughbred racing horse) is the predecessor of Altshuller's TRIZ as a theory of the evolution of artificial systems, and the *alma mater* for Directed Evolution. We will then go on to describe the intellectual history of TRIZ Technological Forecasting and its evolution into I-TRIZ's Directed Evolution. In this section we will also try to show why, although heavily influenced by TRIZ Technological Forecasting, Directed Evolution attempts to answer a fundamentally different question. We shall than briefly explore the underlying logic of Directed Evolution and discuss why we think it is so effective, then conclude with a few thoughts on the implications of DE for business leaders.

I-TRIZ, science and the search for general principles: Reductionism as an approach toward understanding complexity and Darwinian-style Directed Evolution

Any grand, synthesis-oriented attempt to find a "unified theory" of the evolution of artificial systems, such as the applied research program of Directed Evolution, demands a few words by way of an introduction on the general nature of such efforts. This is where we begin. In a thought-provoking book entitled *Consilience: The Unity of Knowledge* (1998), one of the twentieth century's greatest thinkers, Edward O. Wilson of Harvard University, made the following observation:

> "There have always been two kinds of original thinkers: Those who upon viewing disorder try to create order, and those who upon encountering order try to protest it by creating disorder. The tension between the two is what drives learning forward. It lifts us upward through a zigzagging trajectory of progress. And in the Darwinian contest of ideas, order always wins; because – simply – that is the way the real world works." (Wilson, 1998: 46).

Wilson's book calls for scientists to aim at such a unity of knowledge in the natural, human and social sciences. His call is founded on the conviction that everything in our world is organized in terms of a small number of fundamental natural laws which underlie *every* branch of learning. Extreme post-modern philosophical views suggesting that reality is a state constructed by the mind, rather than perceived by it, are being snowed under today by an ever-growing flood of interdisciplinary research efforts attempting to identify unifying organizing principles in the natural, human and social sciences. In this sense, according to Wilson, the cutting edge of science is reductionism: it is the search strategy employed to find a point of entry into otherwise impenetrably complex systems. Complexity is what interests scientists in the end, not simplicity. (Wilson, 1998:58). Reductionism ("simplicity") as a research quest is consistently proving itself to be a productive strategy to understand complexity.

Take Murray Gell-Mann as an example. As a theoretical physicist, Murray Gell-Mann has explored nature at its most fundamental level. His achievements include the 1969 Nobel Prize for work leading up to his discovery of the quark – the basic building block of all atomic nuclei throughout the universe. But Gell-Mann, with lifelong interests in fields that seek to understand existence at its most complex (natural history, biological evolution, the history of language, and the study of creative thinking), employs his observations to tie the fundamental units of understanding from theoretical physics to the complexity of cultural systems. These seemingly disparate pursuits come together in Gell-Mann’s current work at the Santa Fe Institute, where scientists are investigating the similarities and differences among complex adaptive systems – systems that learn or evolve by utilizing acquired information. These include a child learning his or her native language, a strain of bacteria becoming resistant to an antibiotic, the scientific community testing new theories, or an artist implementing a creative idea. In his book *The Quark and the Jaguar: Adventures in the Simple and the Complex* (1994), Gell-Mann tells his own story of finding the connections between the basic laws of physics and the complexity and diversity of the natural and the cultural world. The simple: a quark inside an atom. The complex: a jaguar prowling its jungle territory in the night. Exploring the relationships between them becomes a series of exciting intellectual adventures as well as a source of practical knowledge.

Still, as Wilson points out, the unification agenda does not sit well with a few professional philosophers. They will draw this indictment towards such efforts attempting to reduce complexity: “conflation, simplism, ontological reductionism, scientism, and other sins made official by the hissing suffix.” To this Wilson replies: “I plead guilty, guilty, guilty. Now let us move on, thus.” (Wilson, 1998:9) Reductionism, continues Wilson, is the way to understand complexity in both natural and cultural systems. The love of complexity without reductionism makes art; the love of complexity with reductionism makes science (Wilson, 1988:58).

Seen from this perspective, I-TRIZ in general, and Directed Evolution in particular, are a “reductionist-flavored” effort aimed at a better understanding of the complexity of artificial systems. Indeed, I-TRIZ practitioners are interested in the *complexity* of technological systems but realize that the way to grasp this complexity is by *reducing* it to a set of generic, well-understood, core operating principles. These principles are based on the following fundamental postulates: The emergence and implementation of innovation are not random or haphazard (as they might appear), but rather are dictated by certain general evolutionary patterns governing the creation of artificial systems.[5]

These patterns can be revealed through study of the history of innovation in various cultural areas, including technology, the arts, social life, etc. Once revealed, patterns can be purposefully applied to predict possible evolutionary "paths," as well as potential dangers associated with these paths, for a given technological system. Knowledge of these evolutionary patterns may be used to map past, present and possible future scenarios of a relevant technology *vis-à-vis* a given business/market ecology, then "direct" (or force) the evolution of that particular technology to a chosen scenario. The strategy of directing the evolution of a system moves us from guesswork, prediction and forecasting to the application of a structured method that includes both analytical and knowledge-base (software-based) tools. Once a likely preferred evolutionary future for a particular technology is selected, it is possible to direct the evolution of a given technological system from the present into the future to realize this selected future.

Past attempts to identify general patterns in the natural world have resulted in such great syntheses as Newtonian physics, which reduced enormous complexities into a set of well-defined core principles,[6] and the visionary work of Dmitry Ivanovich Mendeleyev, who formulated the Periodic Table (1869), considered one of the most useful and important generalizations (reductions) in all of science. Mendeleyev was the first chemist to understand that all elements are related members of a single, ordered system. From his table he predicted the properties of elements then unknown, three of which (gallium, scandium, and germanium) were discovered in his lifetime. Knowledge of a few basic patterns and operating principles enables an understanding of complexity (the world of

[5] Following Zlotin and Zusman (2001:21), we refer to an artificial system as any system created by humans, including: *Technical systems*: any machine, device, equipment, manufacturing process or other process related to design and production, utilization of materials, etc. *Social systems*: various groups of people, organizations and associations, management systems, legal systems, etc. *Intellectual systems*: religious and philosophical concepts, scientific theories and hypotheses, arts, etc. *Service systems*: education, medicine, entertainment, etc.

[6] In two of his most famous works: *Philosophiae Naturalis Principia Mathematica* (1687) and *Opticks* (1704), Newton helped define the laws of gravity and planetary motion, co-founded the field of calculus, and explained the laws of light and color, among many other discoveries.

chemistry) and even allows for effective predictions.[7] Similarly, basic elements and operating principles of more complex and higher-order systems, such as plants and animals (biological systems), have been discovered over the past 200 years. These scientific efforts started with Linnaeus (*Systema Natura*, 1735) and Darwin (*Origin of Species*, 1859), continued with the discovery of the structure of DNA by Watson and Crick (1953), and recently reached the achievement of the Human Genome Project, a coordinated worldwide effort (completed in 2000) to determine the precise arrangement of nucleotides in human DNA.

Yet, beyond static classifications (e.g., the Linnaean classificatory system) and the identification of generic core elements (e.g., DNA) of the complex systems which living plants and animals are, there have always been efforts to unveil and conceptualize the general evolutionary patterns associated with the dynamics of living systems. A major encouragement to this line of thinking came from geology and especially from Charles Lyell, who later became a major influence on Darwin. As Lyell observed in his *Principles of Geology* (1830), geology is essentially historical in character: “Geology is the science which investigates the successive changes that have taken place in the organic and inorganic kingdoms of nature; it enquires into the causes of these changes, and the influence which they have exerted in modifying the surface and external structure of the planet.” Much of our knowledge of geologic materials, features, and past events is based on the observation of currently active processes. The concept of “the present as the key to the past” (which inspired Lyell), developed during the Scottish Enlightenment abut half a century earlier. During the same period it was recognized that observations of current geologic processes can be used to predict future geologic events. David Hume wrote in 1777: “…all inferences from experience suppose… that the future will resemble the past…” In 1788, James Hutton wrote: “… from what has actually been, we have data for concluding with regard to that which is to happen thereafter.” These notions lead to the dynamic line of thinking adopted by Darwin a century later. Some 200 years later they led to Directed Evolution.

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[7] On the intellectual history of the Periodic Table see van Spronse, 1994. For a good popular account of the logic behind the Periodic Table and how it was discovered by Mendeleyev, see P. W. Atkins, 1995.

Darwin went beyond static classifications of the living world in his *The Origin of Species* (1859) and was followed by Gregory Mendel's discoveries of the Genetic Laws in the 1860s. Although Darwin is best known for his theories on the mechanics of change in nature (natural selection), his ideas on "directed evolution" are of primary importance to our discussion in more than one sense, since Darwin was also one of the first to discuss ideas related to the evolution of artificial systems.

Darwin was mostly interested in mechanisms of change and evolution in living systems. In the cultural milieu of his time,[8] he first had to prove (and did) that organisms do in fact change over time. Once this was established, however, the questions remained: 1) How do living things change? 2) Why do they change? and 3) What can account for this constantly changing diversity of the living world? Darwin had his own ideas about such mechanisms.[9] Ernst Mayr, a Harvard professor called by some "the next best thing to Darwin himself," attempted to summarize the essence of the idea of evolution in his grand synthesis entitled *What Evolution Is* (2001). Mayr explained the following: In the *Origin of Species* Darwin presented his idea that species evolve from more primitive species through the process of natural selection, which works in nature. In his account of how natural selection occurs, he pointed out that not all individuals of a species are exactly the same but, rather, individuals have variations and that some of these variations make their bearers better adapted to particular ecological conditions. Darwin also pointed out that most species produce more eggs and offspring than ever reach maturity. He theorized that well-adapted individuals of a species have more chance of surviving and producing young than the less adapted, and that over the passage of time the ones that are less adapted are weeded out. The accumulation of adaptations to a particular ecological way of life leads – if there is a geographic split of the population – to the development of separate species, each adapted to

[8] Some 259 years earlier, Giordano Bruno paid dearly for stating his ideas in the wrong time and place. Hearing the ideas of Copernicus about the nature of the universe sent Bruno into a veritable frenzy of philosophical thought. If the Earth was not the center of the universe, and all those stars clearly seen in the night sky were also suns, then there must exist an infinite number of Earths in the universe, inhabited by other beings like ourselves. This idea about the universe did not sit well with the Church. On February 19, 1600, he was driven through the streets of Rome, stripped of his clothes and burned at the stake.

[9] So did Alfred R. Wallace, who in 1858 sent Darwin a letter which contained the same basic explanatory principles to which he had arrived independently of Darwin.

its own particular ecological living space. And what an idea it was! As the famous geneticist Theodosius Dobzhansky (1900-1975) observed, Darwin's version of evolution is the cornerstone of biology and is central to an understanding of both living and extinct organisms. Dobzhansky's statement that "nothing in biology makes sense except in the light of evolution" has been repeated in hundreds of articles arguing for a central place for Darwinism in all areas of science education, including medicine, agriculture and biotechnology. Nevertheless, it took Darwin some 20 years before he could explain these principles to others.[10] Sure, there was the religious aspect with its associated "fear factor" – but that was not all the story. The realization that highly complex and diverse systems – living things – obey a few simple basic patterns and principles that govern and control change was inconceivable and very hard to explain and demonstrate. Interestingly, in order to demonstrate and establish his ideas about this mechanism (evolution by means of natural selection), Darwin first embarked on a study of the mechanisms related to the "directed evolution" of artificially constructed biological systems, better known as "evolution by means of artificial selection" or, as Darwin calls it in chapter one of *Origin of Species*, "variation under domestication."[11] Here, in Darwin's words, is the essence of the idea:

> "I shall devote the first chapter of this abstract [*The Origin of Species*, Y.M.] to variation under domestication. We shall thus see that a large amount of hereditary modification is at least possible; and, what is equally or more important, we shall see how great is the power of man in accumulating by his selection successive slight variations. I will then pass on to the variability of species in a state of nature." (Darwin, 1859: 32-33).

In short, Darwin went on to study how pigeon breeders actually direct the evolution of a given rock pigeon and turn it, in just a few generations, into an artificially constructed

[10] By 1842 Darwin was confident enough in his theory to draft a short sketch, and in 1844 he composed a longer version, which he showed to his friend, botanist Joseph Dalton Hooker. Wary of presenting his theory to the public, Darwin spent the next decade concentrating on a treatise on barnacles, in which he hinted but did not actually say that species were the product of natural selection. In the meantime, the intellectual atmosphere in England altered, and discussions about evolution became commonplace. See Gould, 1977: chapter 1 and Quammen, 2006)

[11] See also R. Dawkins' discussions on the implications of Darwin's formulations on cultural theory (Dawkins, 1976, 1982, 1985). See also Blackmore, 1999.

new sub-species which is the product of, and adapted to, the culturally-skewed demands of a “market” such as beauty:

> “Let us now briefly consider the steps by which domestic races have been produced, either from one or from several allied species... One of the most remarkable features in our domesticated races is that we see in them adaptation, not indeed to the animal’s or plant’s own good, but to man’s use or fancy.” (Darwin, 1859:66)

The great power of this principle for any pigeon or dog or horse breeder is in *selecting a future (based on a trait) and directing the evolution of that species towards that end by selective breeding*. The selecting power is a market that often rewards speed and early maturity (in the case of racing horses) or hunting and chasing properties (in the case of hunting dogs):

> “We can not suppose that all the breeds were suddenly produced as perfect and as useful as we now see them; indeed, in many cases, we know that this has not been their history. The key is man’s power of accumulative selection: nature gives successive variations; man adds them up in certain directions useful to him. In this sense he may be said to have made for himself useful breeds.” (Darwin, 1859:67)

In this “directed evolution” of biological systems, a future among many possible ones is selected in advance and a careful breeding strategy is used to reach that future. The important point here is this: you select a future and *direct* the evolution of your animal or plant “product” to that end:

> “The great power of this principle of selection is not hypothetical. It is certain that several of our eminent breeders have, even within a single lifetime, modified to a large extent their breeds of cattle and sheep… Breeders habitually speak of an animal’s organization as something plastic, which they can model almost as they please…the principle of selection as “that which enables the agriculturist, not only to modify the character of his flock, but to change it altogether. It is the magician’s wand, by means of which he may summon into life whatever form and mould he pleases.” (Darwin, 1859: 68).

And what is the “ROI” according to Darwin (1859:68)? Note in the quotation below how ROI is measured in terms of intellectual capital:

> "What English breeders have actually effected is proved by the enormous prices given for animals with a good pedigree; and these have been exported to almost every quarter of the world…. its importance consists in the great effect produced by the accumulation in one direction, during successive generations, of differences absolutely inappreciable by an uneducated eye – differences which I for one have vainly attempted to appreciate." (Darwin, 1859: 67).

In the same paragraph Darwin even goes on to discuss the sometimes difficult nature of generating innovation and valuable IP:

> "Not one man in a thousand has accuracy of eye and judgment sufficient to become an eminent breeder. If gifted with these qualities, and he studies his subject for years, and devotes his lifetime to it with indomitable perseverance, he will succeed, and may make great improvements; if he wants any of these qualities, he will assuredly fail. Few would readily believe in the natural capacity and years of practice requisite to become even a skilful pigeon-fancier."

These paragraphs represent, in my view, one of the earliest formulations of how Intellectual Property (IP) can lead to Intellectual Capital (IC) as an engine for profit in free-market contexts.

Only after demonstrating the enormous power of directed evolution (evolution by means of artificial selection) to generate wishful (and profitable) futures, did Darwin turn to discuss natural selection:

> "Slow though the process of selection may be, if feeble man can do much by artificial selection, I can see no limit to the amount of change, to the beauty and complexity of the coadaptations between all organic beings, one with another and with their physical conditions of life, which may have been effected in the long course of time through nature's power of selection, that is by the survival of the fittest." (Darwin, 1859:179).

Directed Evolution for technological systems shares many similarities with Darwin's approach (*TRIZ in Progress*: 213; Zlotin and Zusman, 2001). In biology there are objective (i.e., not dependent on human involvement) patterns of biological evolution – in I-TRIZ there are objective evolutionary patterns of man-made systems. In biology, knowledge of these patterns allows for the purposeful influence on evolution, forming desirable species of plants and/or animals and controlling population size. In I-TRIZ's Directed Evolution, knowledge of the patterns of man-made systems allows for the purposeful influence on the evolution of man-made systems in desirable directions (*TRIZ in Progress*: 84, 213-215). Directed Evolution is very much like evolution by means of artificial selection, except that it is mainly (not exclusively) applied to technological systems. In this sense, the quests for general patterns and the utilization of these patterns is well in line with similar quests in some of the greatest scientific traditions of the past.

A brief intellectual history of Directed Evolution

As we have tried to show, Charles Darwin should be regarded as the conceptual father of Directed Evolution.[12] Darwin wrote about artificial selection back in 1859, nevertheless, the term Directed Evolution was coined as recently as 1994. What happened in between? We now turn to discuss the later intellectual history of Directed Evolution: an applied theory of the evolution of artificial systems. The "timetable" of DE presented below may be summarized as follows: Darwin is the conceptual father; Altshuller, the creator of TRIZ Technological Forecasting (applied TRIZ), provided the earliest patterns and some of the lines of evolution of what later became Directed Evolution. Zlotin and Zusman and their team developed I-TRIZ (and in the process added numerous lines and restructured some of the patterns) and synthesized it all into Directed Evolution, or applied I-TRIZ. In order to understand the path from Altshuller's patterns to TRIZ Technological Forecasting to Directed Evolution we now turn to a more detailed history of theoretical and applied Directed Evolution.

Directed Evolution is fundamentally rooted in the lifetime research effort of Altshuller, which began in 1946 in the former Soviet Union. The actual institution of Directed Evolution as an applied theory took place nearly five decades later, by a handful of applied TRIZ scientists in the United States. Altshuller (1926-1998) was one of those intellectuals who, to use Wilson's phrase, "upon viewing disorder tried to create order." So

[12] Some consider Lammarkian inheritance (after the notable pre-Darwinian French biologist Lammark) to be a better principle to account for the evolution of artificial systems. This point is beyond the scope of this article, however. For a critical discussion of this view, see: Blackmore, 1999: 59-62).

are the intellectuals of the “Z Team”: Zlotin (Boris), Zusman (Alla) and Zainiev (Gafur), former colleagues of Altshuller and those directly responsible for the concept, method, tools and the name “Directed Evolution.” Currently heading the Ideation Research Group, the largest, most active and advanced conglomerate of TRIZ practitioners today, Zlotin and Zusman are clearly Altshuller’s most influential and prolific successors (*TRIZ in Progress*, 1999). Another “Z” is Zion Bar-El, who, although not directly involved in research, is an honorary member of Directed Evolution’s Z Team for having provided the inspiration, vision and business infrastructure that turned Directed Evolution into a service and product.[13] In more than one way, and as will be shown below, Directed Evolution represents an original and distinct phase in the evolution of I-TRIZ, as well as the heir to TRIZ Technological Forecasting. We shall return to Ideation’s Z Team later; for now we return to Altshuller, the founder of TRIZ Technological Forecasting.

Altshuller laid the theoretical foundation and the research approach for a new way of looking at technological systems. The apparent disorder that needed order was the complex variety of, and relationships between, technological systems. Altshuller took what was known about the nature and dynamics of innovation and combined it with objective (and new) knowledge about how technological systems evolve. This led to the discovery of the patterns that underlie the development of technological systems. In this way Altshuller created order where there was none before.

The roots of Directed Evolution extend to the mid-1950s, when an approach for reckoning the future, called Technological Forecasting (Martino, 1983; Jantsch, 1967, 1972) was under development. The practitioners of Technological Forecasting were looking to answer the following question: “What does the future hold for my product or process parameters?” By the mid-1970s, attempts to answer this question had spawned such techniques as trend extrapolation, morphological modeling, the Delphi process and others, all of which were based on probabilistic modeling of future characteristics of various systems.

[13] In another analogy, as there wouldn’t be *Sgt. Pepper’s Lonely Hearts Club Band* without Brain Epstein and George Martin (the legendary manager and producer of the Beatles), there probably wouldn’t be Directed Evolution as it is today without Zion Bar-El.

By that time, Altshuller's work on TRIZ had set the stage for an entirely new approach to the subject of forecasting the future. Since the late 1940s, his research had revealed strong, historically-recurring tendencies in the development of man-made systems. Altshuller published the first set of patterns of evolution in the spring of 1975, in a seven-page memo distributed among the USSR's most prominent TRIZ schools.[14] The primary TRIZ postulate, that technological systems evolve not randomly but according to objective patterns, yielded an important corollary: *These patterns, once revealed, can be applied to "force" the evolution of a system into its future incarnation before it would otherwise occur naturally.* In other words, the patterns of evolution provided users with predicting power. For example, the pattern entitled *Evolution Toward Increased Dynamism and Controllability* states that technological systems tend to evolve from rigid structures into flexible or adaptive ones. (This pattern can be seen in the development of aircraft wings from rigid to variable-geometry designs.) Accordingly, a design engineer working on a next-generation medical tool is encouraged to use flexible materials to gain new adjustment capabilities.

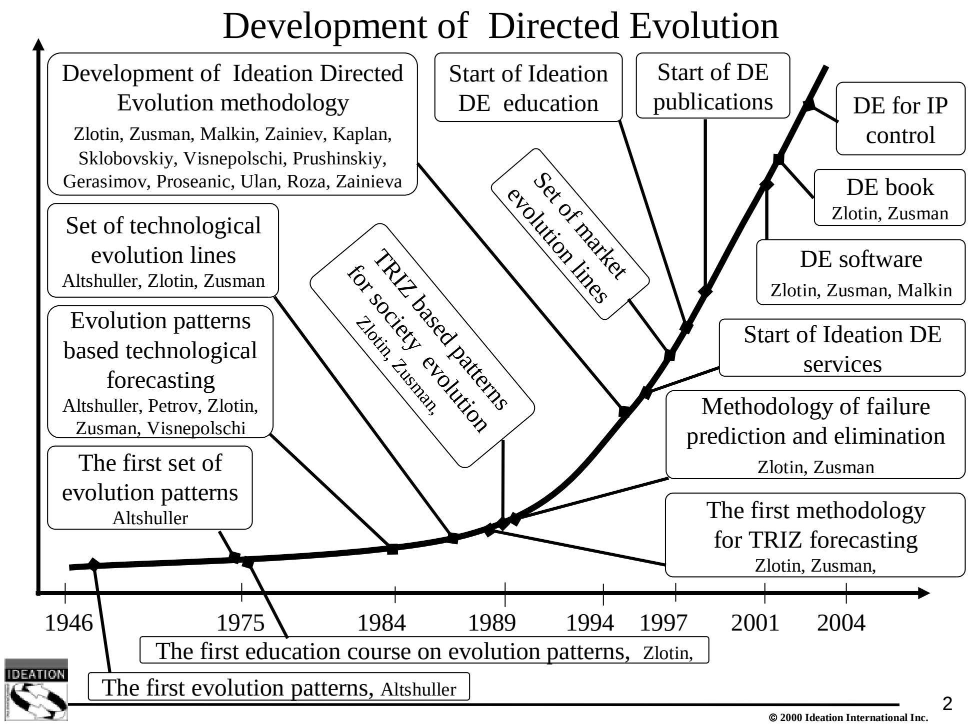
In 1975, Altshuller published the first article on TRIZ Technological Forecasting, based on the patterns of evolution revealed through extensive patent research and systematic studies of the history of technological systems. It was clear that knowledge of the patterns could significantly reduce the number of trial-and-error attempts associated with the development of technological systems, as it could assist in the generation of ideas for developing next-generation products or processes. In the fall of 1975, Boris Zlotin taught the first course on the patterns at St. Petersburg's Public TRIZ University. As part of the coursework, students (many of whom were estimable specialists in various technical areas), analyzed the historical evolution of different systems and attempted to predict the next evolutionary steps using Altshuller's patterns. Over the years, these courses resulted in a substantial amount of new information and an increased understanding of the nature and applicability of the patterns. (For example, certain patterns were found to apply to non-technical areas such as art, organizations, etc.)

[14] These patterns were later included in Altshuller's book *Creativity as an Exact Science*, published (in Russian) in 1979.

By 1981, Altshuller and Zlotin were jointly teaching TRIZ, and the patterns of evolution, to technical specialists and inventors throughout the USSR. Also attending the seminars were experienced TRIZ specialists who wished to further their knowledge. Among these was Alla Zusman, whose research had included attempts to find relationships between the patterns of evolution and the laws of dialectics (the works of Hegel and Engels were popular in the USSR at that time). In 1982, Zlotin, Zusman and others founded the Kishinev TRIZ School in Moldova, whose primary research focus was the patterns of evolution. The first in-depth applications of TRIZ Technological Forecasting occurred in 1983 with the work of three Kishinev members: Vladimir Petrov, Boris Zlotin and Svetlana Visnepolschi.[15] A year later, Zlotin, Zusman and Visnepolschi introduced a step-by-step algorithm for TRIZ Technological Forecasting.

TRIZ Technological Forecasting represented a proactive approach to the problem of understanding the future. Moreover, it was a realization that the future was in a way predictable, as it behaves in accordance with certain predetermined, apparently repetitive, patterns. These patterns were few in number and general in nature, however, and therefore offered only general forecasting power. In 1985, Altshuller, Zlotin and Zusman defined the first lines of evolution – more detailed evolutionary steps within a pattern. This enabled more accurate, “tailored” scenario building for the evolution of a system: once the system’s current position on a line is identified, the possibility of transitioning to the next position can be assessed. The question posed by traditional forecasters had become, “What changes should be made to move my product or process to the next position on a specific line of evolution?”

[15] Petrov applied TRIZ Technological Forecasting to the development of welding equipment, Zlotin and Visnepolschi to the development of water pumps.



Through the late 1980s and early 1990s, activities related to “technical” TRIZ (TRIZ applied to technical problems) declined due to the rapid degradation of the Soviet economy, Altshuller’s battle with Parkinson’s disease, and the emigration of leading TRIZ specialists to the United States, Israel and Europe.

In 1992, Zion Bar El heard about TRIZ and, together with the people of the Kishinev School, established Ideation and its Research Group. The era of I-TRIZ had begun. Since Altshuller’s death in 1998, the Ideation Research Group, which collectively represents more than 300 years of joint TRIZ experience, has been the *de facto* center of gravity for TRIZ R&D and application. It is in this context that Directed Evolution emerged, having been introduced in the mid-1990s by Zlotin, Zusman, Zainiev and their colleagues to refer to the complex of works related to the management and control of technological evolution. Today, Directed Evolution is seen as a systematic approach aimed at identifying a comprehensive set of potential evolutionary scenarios for both technological and socio-cultural systems, and the use of this knowledge to “direct” the evolution of artificial systems into desired futures.[16] The question posed by Directed Evolution practitioners can therefore be stated as, "Which evolutionary scenario, selected from a comprehensive set of scenarios based on the lines of evolution, will make my system a winner?" Granted, this is an intellectually-driven question – curious scientists searching for order – but having been inspired by the ideas of Adam Smith (1759) and Michael Porter (1985), it employs competitive advantage jargon and is framed with free markets in mind. It is about competing and winning. Clearly, TRIZ (in the form of I-TRIZ) has earned its American citizenship.

With a decade (1994-2004) of research and application behind it, Directed Evolution is equipped with the theory and the methodology that can answer this new question. Today, I-TRIZ in general and Directed Evolution in particular represent a powerful synthesis of effective approaches to creative problem solving and the control of technological evolution. It is a classic "the sum is greater than the parts" situation. In addition to Altshuller's classical TRIZ and its later improvements by the Kishinev School, there were two other directions that eventually converged with TRIZ to create the full I-TRIZ scheme. The first can be termed "Osborn's Direction,"[17] aimed at decreasing psychological inertia, activating human motivation, and organizing effective teamwork via such methods as brainstorming (Osborn), Synectics (Gordon), Fundamental Design Method (Matchett) and the Six Thinking Hats (DeBono). The second broad direction of influence on I-TRIZ can be called "Miles/Ishikawa's Direction" aimed at the re-structuring of existing knowledge for effective application of the creative process. This direction includes such methods as Value Engineering (Miles), Morphological Analysis (Zwicky), Quality Functional Deployment (Akoa) and fishbone diagramming (Ishikawa). Other sources of inspiration include the Six Sigma approach and an array of failure analysis approaches.

In 1994, the first Directed Evolution services were conducted; a year later the first papers on DE were published. In 2001, the monograph *Directed Evolution: Philosophy, Theory and Practice* by Zlotin and Zusman was published. In that same year, proprietary

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[16] Including products/services/processes, organizations or enterprises, industries and markets. The term "bank of evolutionary alternatives" is used to represent the actual scenarios developed for certain areas/industries that have an important influence on other, less general systems, and are expressed as patterns and lines of evolution.

[17] After Zlotin and Zusman, personal communication, August 2004.

Directed Evolution software was developed for internal (non-commercial) use by the Ideation Research Group. Since 2003, Directed Evolution and other I-TRIZ knowledge has been applied to the validation and enhancement of intellectual property – inventing around patents, strengthening patent protection, and searching for new applications for IP. This new phase of Directed Evolution application is called CIP (Control of Intellectual Property) and is even practiced commercially. All these achievements in theory and application explain why Zlotin, Zusman, Bar El and their colleagues should be credited with creating something truly remarkable on the basis of the more traditional TRIZ Technological Forecasting.

Wilson's book *Consilience: The Unity of Knowledge* (1998), with which we began this article, calls for a search of laws in the social sciences and for a grand theory that will unify the life sciences with the social sciences. Wilson has areas such as sociobiology in mind – syntheses that combine and tie knowledge of biology (e.g., patterns of behavior in social insects) to knowledge of sociology and cultural systems (social structures, social roles, patterns of social interaction, diffusion of ideas and memes, etc.). But before turning into inter-discipline convergence (or in Wilson's terms, "consilience"), it seems that social science as a body of knowledge seeking to identify patterns and principles by which cultural systems operate should come up with its own contribution. Wilson is extremely critical on the achievements of social scientists on this matter (Wilson, 1998), and he is not alone.[18] There were, nevertheless, major attempts to come up with such principles and patterns. The social and behavioral sciences have always searched for laws in areas such as psychology (e.g., personality theories), sociology (e.g., functionalism) and especially anthropology (e.g. Cultural Materialism). In the latter discipline, the possibility of patterns and laws within cultural systems has long been a major research question[19] as evidenced by, for example, the 1960's search for repetitive patterns in the evolution of societies (Fried, 1967; Service, 1971), the efforts to decode the DNA of such processes as the rise complex society and urbanization (Lamberg-Karlovsky and Sabloff, 1995), the earlier quests to identify patterns of cultural growth (Kroeber, 1944), and the search for general laws and principles that epitomize the nature of culture (George Peter Murdock, 1965). The

[18] See, for example, Pinker (2002) for a highly critical review and further literature.
[19] See Adam Kuper (1994) for a good historical review of such questions in anthropology.

wave of post-modernity washed away most of these efforts, but fortunately we are back on track and, in this author's view, I-TRIZ is one of the better ways to approach this search.

So, we have come to this. From its first incarnation as a technique for technological problem solving, I-TRIZ is becoming a promising source of knowledge and tools for controlling the evolution of technological systems. Subsequently, I-TRIZ's Directed Evolution has been extended to non-technical areas, including the areas of social and organizational evolution.[20] In fact, while maintaining part of its old name, I-TRIZ has been transformed into the *Theory of Evolution of Artificial Systems (TEAS),* on which basis it became possible to develop a new methodology for managing/controlling evolution – this is the process called *Directed Evolution.*

The praxis of Directed Evolution and what makes it work? Comments on the logical visibility of DE as a form of applied theory of artificial systems

Directed Evolution is a praxis-oriented theory based on over 50 years of inductive research of over two million patents and a continuous, decades-long study of the history of technology. These studies tell us that the emergence and implementation of innovation and R&D efforts are not random or haphazard (as they might appear), but rather are dictated by the evolutionary patterns that govern the creation of artificial systems. Thus, Directed Evolution is a systematic process to predict future generations of a system by inventing them. It replaces the guesswork of forecasting with a strategic decision-making process that is based on potential evolutionary scenarios developed by applying proven evolutionary patterns/lines, followed by the implementation of one or more of these scenarios in accordance with the decisions made. As described by Zlotin and Zusman (2001), at the heart of DE are the patterns/lines of evolution, so a brief survey of the basic patterns is warranted.[21] As stated earlier, the patterns of evolution represent a compilation of strong,

[20] Up until now, most of the theory has been generated and tested in contexts related to technological systems. While other more complicated artificial systems, such as social systems, seem to behave in accordance with Directed Evolution principles, social systems are beyond the scope of this paper. For a discussion of TRIZ application to non-technical systems see: Boris Zlotin, et al., "TRIZ Beyond Technology," proceedings from TRIZCon2000 (Worcester, Mass.: The Altshuller Institute for TRIZ Studies, 2000), p. 135. Also published in *The TRIZ Journal* (www.triz-journal.com), January 2001.

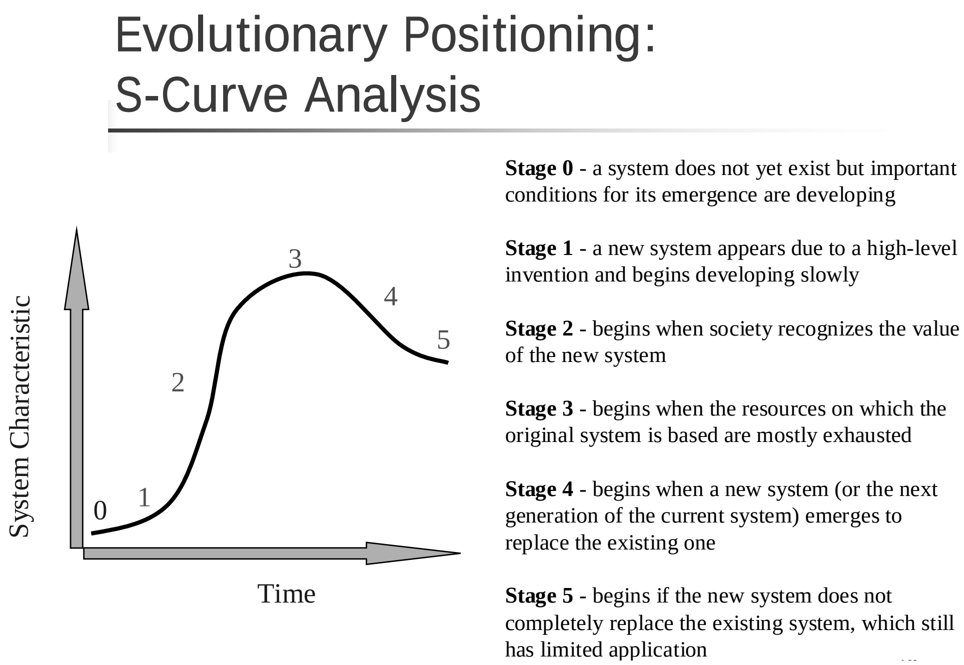
[21] See also *TRIZ in Progress*, Appendix 13 (Ideation International, 1999).

historically-recurring tendencies in the development of man-made and natural systems. Most patterns contain lines of evolution describing, in greater detail, the typical stages that a system follows in the process of its natural evolution.

Currently, the there are between eight and twelve patterns, depending on the application and tool being used. Three of these patterns originated with Altshuller and are expressed in his (translated) words.[22] Two of Altshuller's patterns have been generalized and expanded, and three to seven patterns added. The patterns used by the Ideation Research Group include three "mega-patterns" (Stages of Evolution, Evolution Towards Increased Ideality, and Evolution Toward Non-Uniform Development of System Elements). This discovery occurred as a result of the analysis of hundreds of thousands of innovations spanning different areas of technology.

The first mega-pattern, Stages of Evolution, was known in other fields of science and technology as the classic S-shaped curve, and only needed refinement in terms of TRIZ findings. Implicit in the S-curve are assumptions of slow initial growth, subsequent rapid growth, and, eventually, declining growth. This pattern, which states that all systems have characteristic lifecycles along which they evolve (from birth to death) is considered a "generic" pattern, as it describes evolution at the macro-level. The TRIZ version of the general S-curve is described in terms of the five stages shown in the figure below.

[22] Altshuller's patterns are described in *Creativity as Exact Science* (New York: Gordon and Breach Science Publishers, 1984).



The essence of the second mega-pattern, Evolution Toward Increased Ideality, is the realization that every system performs functions which generate useful effects and harmful effects, and that the general direction for system improvement maximizes the ratio of useful to harmful effects. In other words, systems evolve in the direction of increasing *ideality* – they become smaller, less costly, more energy efficient, pollute less, and so on. In principle, market forces and culturally-bound optimization forces are responsible for increasing a system's ideality. We will discuss this mega-pattern at some length later in this article since it is at the heart of I-TRIZ and Directed Evolution.

A third mega-pattern states that, in the process of becoming more *ideal*, the development of system elements will tend to be non-uniform. Since each system component has its own S-curve, and since different components usually evolve according to their own schedules, different system components reach their inherent limits at different times, resulting in contradictions. The component that reaches its limit first "holds back" the overall system (640K memory for personal computers, for example). The elimination of contradictions allows the system to continue to improve.

Among the remaining patterns is the observation that, in the process of becoming more ideal, a system will tend to follow the pattern of Evolution toward Increased

Involvement of Resources. In other words, as it develops, a system will tend to use more of its existing resources[23] before new ones are added. Compression technologies in telecommunication (ADSL, for example) follow this principle. On-the-fly compression of computer hard drives follows this pattern as well.

Another pattern states that an evolving system will tend to become more dynamic and controllable. Increasing system dynamism allows functions to be performed with greater flexibility and variety. The increasing ability to customize hardware (open architecture) and software (Object Oriented Programming and GUI-based word processors in the PC industry) are good examples.

Another pattern states that a system will pass through cycles of increasing complexity followed by simplification (reduction). Technological systems tend to develop first toward increased complexity (i.e., increased quantity and quality of system functions), and then toward simplification, where the same or better performance is provided by a less complex system. This may be accomplished by transforming the system into a bi- or poly-system. Again, we can recall a PC sound card, modem, and video card installed in slots on the motherboard in the early days of the industry, whereas now these components have become integrated into the motherboard or even the processors.

Other examples of evolutionary patterns exhibited by technological systems include the empirically-observed phenomena that a system will tend to evolve with Matching and Mismatching Elements in order to improve performance or compensate for undesired effects. A typical evolution might be as follows: a) Unmatched elements, b) Matched elements, c) Mismatched elements, d) Dynamic matching and mismatching. In the following example the development of an automobile suspension system follows accordingly: a) Springs attached between wheels and body, b) Shock absorber and spring tuned to damp out impact forces, c) Semi-rigid rubber isolation mounting between the body and shock, d) An active suspension system that automatically adjusts to road conditions.

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[23] A *resource*, according Webster's New World Dictionary, is something that lies ready for use or can be drawn upon for aid. In TRIZ, resources are a major force and enabler of innovation. TRIZ views resources as substances, fields (energy), their properties, functional characteristics and other attributes existing in a system and its surroundings, which can be utilized for system improvement. In TRIZ taxonomy, it is common to differentiate between the following six general types of resources: substance, field, space, time, informational, and functional.

And here is another pattern: In the process of evolving a system will tend to follow the pattern of Evolution Toward the Micro-Level. Technological systems tend to transition from macro-systems to micro-systems. During this transition, different types of energy fields are used to achieve better performance or control. Let us take cooking technology as an example. The development of cooking ovens began with large cast-iron wood stoves, which then evolved into smaller stoves fired by natural gas, then continued to electrically-heated ovens and, at present, microwave ovens.

The last pattern in this set of examples is the Pattern Toward Decreased Human Involvement. This pattern states that systems develop to perform tedious functions that free people to do more intellectual work. Clothes-washing technology is a good example here: What began as a tub and washboard later evolved into wringer washing machines, followed by automatic washing machines and, finally, automatic washing machines with automatic dispensing sub-systems for soap, bleach and fabric softener. The same pattern can be observed in the evolution of writing technology as well (from cuneiform clay writing systems to medieval script writing, to the printing press, typewriter, electric typewriter, and word processor, which has itself developed non-uniformly, according to the pattern described earlier). Interestingly, and as the writing example hints, the more digital technology is embedded into technical systems, the more this evolutionary trend will continue.

There are several questions that we need to deal with here. The obvious first question is: How and why do different technologies follow similar patterns and lines of evolution? After all, what prevents a given technology from taking different directions and following different patterns? The answer lies, it appears, in the basic fact that technologies do not evolve by way of an independent, conscious will (just as natural species do not evolve “into” something but are rather variations “selected for” by natural forces of selection). Technologies, like any other cultural manifestation, are human-driven, whether that human effort is conscious or not. In this sense, they may follow certain cultural dynamics (such as the logic of open market forces, a given rational system that systematically perceives reality in a certain way, or certain fashions that dictate or lead expected associated behaviors). Thus, and in evolutionary terms, technological variations (like genetic variations) only provide opportunities; changing cultural configurations (e.g., markets) that are analogous to natural ecosystems represent the selection agents. In a clear analogy to the evolutionary selection processes, the combination of technological variations with a systematic logic of market selection forces may generate repetitive evolutionary patterns. The legitimacy of searching for (not to mention the very existence of) such general patterns of evolving technological systems is now an established fact, confirmed independently by authorities such as Utterback (1993, 1994), who examined industry transformations – from typewriters to PCs, gas lamps to fluorescent lighting, and Eastman’s amateur photography to electronic imaging – in the search for general patterns that reflected, for example, the differences between assembled products (such as automobiles and typewriters) and non-assembled or homogenous products (Silk/rayon). From here on the logic is simple and powerful. Here is what Daniel C. Dennett has to say about the potential viability of Evolutionary Theory to explain cultural complexity (Dennett, 2000: ix):

> “How can *mindless* Darwinian algorithms cope with such *mindful* culture-makers subliminally sensitive to such issues as whether or not the environment includes many paths for coordinating distributed intelligence? But in fact, evolutionary approaches to such underlying conditions of rationality have been leading the way, illuminating the background conditions for communication, cooperation, the establishment of norms and customs, and other phenomena familiar to students of culture. *The open question is not whether there will be a Darwinian theory of culture but what shape such a Darwinian theory will take*… It is obvious that there are patterns of cultural change – evolution in the neutral sense – and any theory of cultural change worth more than a moment’s consideration will have to be Darwinian in the minimal sense of being *consistent with* the theory of evolution by natural selection of *Homo sapiens.”* (Emphases are mine).

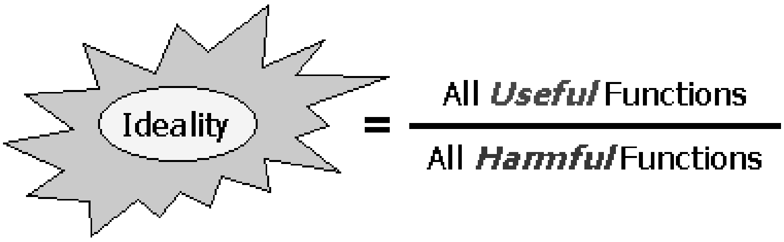
If artificial systems are observed to follow certain repetitive patterns, knowledge of these patterns in advance may be used to guide and control the evolutionary development of given artificial technological systems. This is where we turn next.

Altshuller made the observation that evolving technical systems will tend to become more ideal – that is – be optimized to the maximum. This is a classic equilibrium-based assumption and a sound understanding of the notion of ideality is critical in order to comprehend and follow the logic of Directed Evolution. It is vital to understated that at the core of Altshuller's observations lies the notion that environmental pressures (be they economic/cultural or ecological) push designed technological (as well as natural-biological) systems toward what TRIZ theory calls "ideality." A system is said to approach ideality to the degree that it maximizes the system's useful functions and minimizes its harmful functions. This is why organisms in nature look so perfectly adapted (they are close to ideal) and why certain technological systems become successful (in terms of cultural contexts) within a given temporal and spatial cultural context. As already noted, in the Dialectic-Marxist spirit in which TRIZ was invented, TRIZ seeks to overcome the contradictions that arise, for example, when improving one function of a system leads to deficits in another function of the system. TRIZ seeks to resolve these contradictions not so much by balancing advantages against disadvantages, as in constrained optimization, but by novel win-win solutions that maximize useful functions without (ideally) incurring harmful side-effects. The great obstacle in the way of ideality in artificial systems is psychological inertia, which artificially constricts a solution space rather than opening it to undreamt of possibilities. In biological systems, however, where variation and natural selection do not risk following any pre-existing human paradigm, the products of the process produce the most complicated and inspiring systems. The DE and I-TRIZ processes provide ways to overcome this inertia. In this sense, I-TRIZ is a meme machine that moves ideas from one realm of science to another by the power of analogy. Certainly, ideality's best instantiation is found in biology (according to Altshuller, biology has given us the best of all patent libraries and from here the link to artificial selection is only logical.[24]

This point cannot be over emphasized. Ideality as a principle, whether it is a conscious effort (as in artificial selection or technological systems) or an unconscious one (as in natural selection), is the common thread and the underlying logic of all "rationally optimized" evolving systems. Whether they are natural-biological (in which case ideality is critical – and *is* the enabling reason – for survival, and follows natural selection and other classic Darwinian principles); or whether they are artificial systems (in which case they

[24] Genrich Altshuller, *The Innovation Algorithm: TRIZ, Systematic Innovation and Technical Creativity*, trans. L. Shulyak and S. Rodman (Worcester, Mass.: Technical Innovation Center, 2000), 205-7.

follow principles of artificial selection: optimization of ROI, market supply and demand principles etc.), ideality is the end result of the process. We use the above pattern to define ideality as the ratio of a system's useful functions to its harmful functions:



Functions are the activities, actions, processes, operations or conditions related to a system. A system's useful functions include the following:

- primary useful function – the purpose for which the system was designed
- secondary functions – other useful outputs that the system provides in addition to the primary useful function
- auxiliary functions – functions that support or contribute to the execution of the system's primary useful function, such as corrective functions, control functions, housing functions, transport functions, etc.

A system's harmful functions include all harmful factors associated with the system: the cost to design it, the space it occupies, the noise it emits, the energy it consumes, the resources needed to maintain it, and so on. The core logic of ideality in TRIZ may be summarized as follows: The ideal *machine* has no mass or volume but accomplishes the required work. The ideal *method* expends no energy or time but obtains the necessary effect in a self-regulating manner. The ideal *process* is actually only the process result without the process itself. The ideal *substance* is actually no substance (a vacuum), but its function is performed. The ideal *technique* occupies no space, has no weight, requires no labor or maintenance, delivers benefit without harm, and does so itself, without any additional energy, mechanisms, cost, or raw materials. Clearly this view of the evolution of natural and artificial systems is an idealization that cannot be realized in any concrete physical system. Nonetheless, it serves as a useful regulative principle for designed systems, and its existence may account for the patterns that artificial and biological systems seem to follow.

In general, then, we may look at Directed Evolution as a form of cultural selection theory. That is, it is a theory about phenomena (patterns and lines of technological evolution) which can spread in a society, just as religious rituals, a genre of art, or a certain fishing method do. Any form of cultural selection theory entails three basic processes (Fog, 1999: chapter 3; see also Fog, 1997 and Gabora, 1997). First, the phenomenon must arise. This is called innovation. Next, the phenomenon spreads from one human to another or from one group of humans to another. This is called reproduction or transmission or imitation or diffusion of ideas – or memes.[25] The third fundamental process in the theory is selection. By selection we mean any mechanism or factor that can influence how much or how little the phenomenon will spread. The most obvious kind of selection is the conscious choice exerted by humans operating within a market economy and under culturally-skewed expressions of maximization effort. In a more DE explicit terms, we can say that first, the phenomenon must arise. This is called innovation. Next, the phenomenon spreads from one human to another or from one group of humans to another. This is called reproduction or transmission or imitation or diffusion of ideas – or memes. The third fundamental process in the theory is selection. By selection we mean any mechanism or factor that can influence how much or how little the phenomenon will spread. The most obvious kind of selection is the conscious choice exerted by humans operating within a market economy and under culturally-skewed expressions of maximization effort.

We may briefly summarize the analogies between biological systems, cultural systems and TRIZ thinking as follows:

[25] On memes, see Blackmore, 1999. By using analogies as its main problem-solving vehicle, TRIZ can be seen as a gigantic meme-spreading machine. For a more recent discussion see: Aunger, 2002 and Distin, 2005.

Biology	**Culture**	**I-TRIZ**	**I-TRIZ/DE Example**
Intra-species variation	Memes and ideas	Human creativity, available known history of technology, accumulated knowledge of world patents	Various technologies related to playing recorded music (phonographs, tape recorders, Walkman, CD players, MP3 players, etc.)
Source of variation: mutations and sexual reproduction[26]	Innovation, diffusion of ideas, information technologies in history	I-TRIZ operators, patterns and lines of evolution	New patents and ideas: iPod technology by Apple, Walkman technology by Sony
Natural selection	Markets forces, culturally-perceived rational systems	The quest for ideality in market contexts	Patents and inventions that flourish in the market context (Apple's iPod)
Optimal adaptation to the environment/ ecology	Optimal cultural survival strategies to local ecologies (e.g., domestication of camels by nomads)	Optimal market ROI to business/market ecology	Positive market response/demand (sales, new business modes for the music industry that solve copyright problems)
Evolutionary	Recurring	Follows observed	*Bank of evolutionary*

[26] Sexual reproduction is the best replicating mechanism since it generates a large number of variations.

patterns (example: the tendency toward the independent development of sight organs in different sections of the animal kingdom)	effective adaptive solutions to similar problems (e.g., hunting and gathering as a cultural survival strategy)	evolutionary patterns, which generally lead a system toward ideality	*alternatives* used to direct the development of future portable digital music players.

Implications for business leaders

What are the implications of Directed Evolution for business and commercially oriented design and R&D efforts? There are a number of implications, but the general idea is a simple one. If we think about markets as business ecologies, and if we view various products and services as organisms competing for survival within these business ecologies, being able to direct the evolution of products and services towards optimal adaptation (ideality) in a given market ecology means competitive advantage. In business terms it means: better market adaptation of products and services (ensuring market demand *vis-à-vis* the competition) in a shorter time to market. DE enables an enterprise to envision the future (using the patterns and lines of evolution) and supports a definition of the ideal (desired) direction to pursue. In the process it allows for decision making (assessing and reducing risk, predicting and preventing failures), and protecting intellectual property by identifying appropriate patent strategies and building patent fences accordingly). In the final analysis, DE leads to successful implementation of the whole process by effectively solving new problems and by constantly analyzing and eliminating existing and potential failures.

Past and present I-TRIZ and Directed Evolution research is aimed at exploring the underlying principles in the evolution of artificial systems in general and of technological systems in particular. Since today these theoretical and intellectual pursuits are conducted for the most part within a competitive business setting (funding for Directed Evolution research is provided almost exclusively by revenue generated from successful application of the theory), the theory of Directed Evolution is being developed with a distinct applied flavor and is continuously being (positively) tested in a real-world setting. I-TRIZ insights are being used today to solve practical technical and non-technical problems, to predict and avoid system failures, to control and direct (via R&D efforts) the evolution of given technological systems, and even to generate and secure high Intellectual Property (IP) values for technological systems.

With its methods, tools, algorithms, techniques, and knowledge base, Directed Evolution today supports the following capabilities (arranged in a broad logical sequence). It supports the analysis of the historical and current incarnations of a given system, revealing the basic patterns of its evolution and comparing them with the general patterns.

It also allows for strategic planning, including the identification of long-term objectives and subsequent pre-determined steps in accordance with the patterns/lines of evolution, as well as the invention of new features of one or more future generations. Using DE theory and methodology can reveal potential obstacles in a system's evolution, including dangers, undesired side effects and other problems that might arise or become more prominent as the system evolves (Ideation Failure Prediction[i]). Moreover, DE combined with other I-TRIZ tools allows for quick resolution of problems that must be resolved in order to achieve the goals and eliminate problems that emerge in the evolutionary process. Lastly, DE theory, methodology and tools allows for the selection of innovations to be implemented, based on marketing, technical, social and other evolutionary patterns. Given the above, we believe that DE represents a Third Wave methodology – even a way of thinking – that allows individuals, organizations, nations and humanity as a whole to manage/control its destiny (Zlotin and Zusman, 2001).

The significance of Directed Evolution theory and its application to the domain of innovation – a major engine of growth in the current Intellectual Capital oriented information economy – are potentially striking since the theory attempts to offer nothing short of a systematic "operating system" for innovation. The major elements of this operating system are DE, IPS, AFD and CIP. The relationships between these elements, which constitute an entire operating system for innovation, are as follows: Directed Evolution, the subject of this paper, tells you where you are and where you may want to go. IPS (Inventive Problem Solving) tells you how to do it. AFD (Anticipatory Failure Determination) makes sure you do it right and with minimal failures. Lastly, CIP (Control of Intellectual Property) makes sure you gain maximum ROI in the process.

The I-TRIZ Operating System for Innovation

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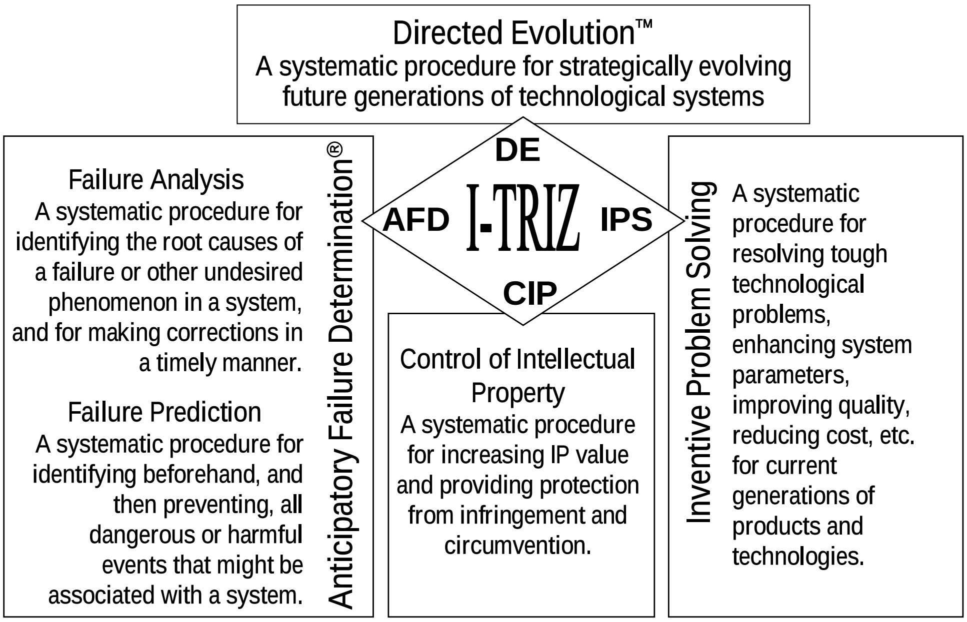

The IPS area is meant to support the identification, definition, and solving of technological problems as well as the technological-engineering development of existing and planned systems. The problem solver who must improve and/or plan a new system is conducted along a work path supported by software designed to aid with the rapid and optimal detection, and speedy solution of, fundamental planning problems. The AFD area is designed to support the location, diagnosis and anticipation of failures in existing and planned systems (Kaplan et al, 1999). The problem solver needing to identify failures in an existing system or to apply preventive anticipation (debugging) of failures in a new or planned system is guided along a software-supported work path constructed to allow him or her rapid and optimal detection of failures and their effective solution. Users of the AFD method are asked to engage in reverse thinking: they become “saboteurs,” systematically testing how to wreck the system in the most efficient way. This entails the use of software tools that support the systematic mapping of potential causes of failures in order of importance and probability, and automatically directs users to those parts of the knowledge base identified by the system as especially relevant to solving the problem.

The CIP (Control of Intellectual Property) part of I-TRIZ concerns the expansion and structuring of IP by way of patent fences (a means of passive protection that consists of a set of patents that protects a product and/or technology, preventing or deterring attacks on a business by competitors) and patent blocks (proactive protection that consists of a set of patents that protects a market, preventing attacks from competitors and/or allowing a company to profit from the success of its competitors by licensing agreements, etc.). Both patent protection and maximization strategies can provide a relatively short-term monopoly or a financial benefit from IP licensing. Recent discussions in the area of Business Processes Management (Smith and Fingar, 2003) address the redesign of core business processes using IT. In a world where enterprises try to sell more and more intellect and less and less material, where intellectual capital is the main generator of income, the central core of business processes is R&D and innovation. Directed Evolution provides just that: a new operating system (a new holistic business process) for innovation. As this new operating system comes equipped with software tools and is supported by IT, it is Business Process Management at its best. It is a Third Wave operating system for innovation.

In business terms the bottom line should be clear. The capabilities and opportunities offered by Directed Evolution translate into the power to drive users to the position of market and technological leadership. Directed Evolution does this by its unique ability to provide the capabilities for strategically mapping technological opportunities, creating breakthrough technologies, opening new markets, capturing reusable proprietary knowledge, and protecting intellectual capital/property.

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