STUDIES IN EMERGENT ORDER VOL 7 (2014): 184-206

Innovation, Complex Systems and Computation: Technological Space and Speculations on the Future

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Introduction

This study puts forward a theoretical framework for understanding the critical role of technological innovation in modern economies. The authors also suggest certain mechanisms by which economic possibilities and, by extension, "life opportunities" can be expanded in ways not heretofore considered. Specifically, this essay shows how the theoretical framework of CAS (Complex Adaptive Systems) can be used to understand both how innovation occurs and how it can be accelerated.

We begin with a discussion of the theoretical framework and assumptions motivating our analysis. This is covered in Part Two. Part Three provides detailed discussion of how the assumptions of self-organizing complex adaptive systems (CAS), integrated with other work done in economic theory involving recombinant growth theory, can provide a framework for understanding how technological evolution occurs and how such evolution can be accelerated. More specifically, we wish to argue that for the first time the possibility exists for the development of self-ordering technological systems that promote accelerated growth. In other words, advances in computation and artificial intelligence combined with our understanding of complex systems, can lead to a rapid acceleration of technological innovation. This is elaborated upon in Part Four, which discusses the Theory of Computational Equivalence. The paper concludes (Part Five) with some final thoughts and observations.

Background and General Framework

What explains why human technological progress, over the course of millennia, moved at a virtual snail's pace until only the last few centuries? In particular, why does progress appear to be accelerating only since the beginnings of the industrial and scientific revolutions? The scientific and industrial revolutions are obviously critical to understanding the burst of innovation and growth. But at a deeper level, something else is occurring. When one looks "underneath the hood," what is the exact mechanism of growth and innovation?

The field of economics, in spite of its critics, has made great contributions to our understanding of complex social interactions. However, with a few notable exceptions, economics has not offered any broad theory that would explain the secular increase over time in goods and services or, more specifically, technological innovation (Kauffman 1993: 387-404; 2000: 211-241).

Economics has concentrated many of its intellectual resources on developing catallactic theories of economic growth, which does represent part of the process with which we are concerned. However, exchange-based theories of growth do not explain how new economic objects, or new goods and services (or innovations), come about. After all, an economy can grow merely through increases in the amount of goods that exist at a given time. It is conceivable, for example, that a society could double its GDP merely by doubling all the goods that exist at a particular point in time. But to do so would not yield any qualitative change in the well-being of citizens, as no advances in innovation would be observed. The U.S. and other nations are wealthier in 2013 than in 1913 not because we have more of the same, but because we have more kinds of goods available. So how does innovation, at some "deep" level, occur?

Neoclassical growth theory, as developed by Solow (1955), envisioned growth as being determined by inputs of labor and capital, with technology representing an exogenous factor in the model. Scholars such as North (1991) have explored the role of social and economic institutions, i.e., the rule of law, property rights, and other elements, to explain why some countries are prosperous and others are mired in poverty. Schumpeterian or neo-Schumpeterian models of growth assume economic progress comes from change, or the decline of old technologies and replacement with new technologies (Schumpeter 1942). Neo-Schumpeterian models that seek to ground our understanding of economic growth within evolutionary models that emphasize the role of knowledge, technology, and entrepreneurship have found significant favor among some economists in recent years (Antonelli 2003; Nelson 2005; Nelson and Winters 1982).

Arrow (1962) recognized the importance of "learning by doing." That is, innovation leads to spillover effects in which those not part of the innovation process learn about it, as in the process of replantation, or development improvements. His work, which comes as close as standard economics has come to our own concerns, is related to Romer's (1986, 1990) critical work in endogenous growth theory, which builds on Arrow. Romer demonstrates in a rigorous mathematical way how ideas, i.e., innovations, are important to growth. These innovations become in a way collective goods, the benefits of which are, in large part, indivisible in that no one can be excluded from sharing in its benefits, even in the presence of patent law and other legal institutions.

Complex Adaptive Systems/Spontaneous Orders. Spontaneous orders are kinds of complex adaptive systems precisely because they adapt, as a whole, to the products and presence of other spontaneous orders. The market, for example, adapts to the presence of a new technology created within the technological order. The new technology is a new product, creating demand for it and affecting demand for other products. In turn, the success or failure of a new technology in the market will affect the direction of the technological order itself. Thus, we see each order—market and technological—constantly adapting to each other.

The basic theoretical framework for the arguments made in this paper derives from the theory of complex adaptive systems, or spontaneous order. "Spontaneous order" is a crucial term in Hayek's (1973; 1988) lexicography, originating with Hayek (1945) and Polanyi (1951). The term is integrally related to the principal of distributed intelligence; that is, markets are able to do what no single dictator or central planning board actively can do, which is to make countless decisions regarding supply, price, investment, and other decisions in a market. Rather, such decisions are left to the decentralized and disaggregated plans of countless individuals, out of which comes spontaneous order. In other words, spontaneous order is a self-organizing system, typified by dynamic network structure. It is a species of complex adaptive system (CAS) known as a transformative complex adaptive system (TCAS). A transformative complex adaptive system has a scale-free network structure and is capable of passing through a far-from-equilibrium state as it moves from one equilibrium state to another, with a resultant S-curve. An organization, on the other hand, is a more standard complex adaptive system, and would be typified by hierarchical network structures. Each is a different kind of "action space," with different outcomes based on the different network structures and different values found in each. Each is the unintended consequence of each person attempting to realize their own goals. Spontaneous orders are thus the result of human action, but are not of human design (Hayek 1973: 37). As previously stated, markets are an important example of a self-organizing system. Within the market order, a few simple rules govern the behavior of individuals and their interactions with spatially or temporarily proximate co-participants, yielding a highly complex, variegated structure that functions in ways that would not be possible if some central authority sought to mimic or replicate the market process through diktat.

One can imagine the kind of processes to which we refer using Kauffman's vision of the economy (or what he refers to as the econosphere) as an analog to the biosphere. The biosphere is, for Kauffman, "a self-consistent co-evolutionary construction of autonomous agents making livings, the natural games that constitute those livings, and the search mechanisms that allow such modes of living to be persistently mastered by adaptive natural selection" (Kauffman 2000: 75).

Similarly, the econosphere is the human extension of the biosphere. Kauffman uses the simple example of the advantages of "trade" or catallaxy (exchange) to make the point. He takes a very simple economy where two agents each have different endowments (to use his example, where two agents each possess apples and pears, but in different ratios) and where the welfare (utility) of each can be improved through trade. Similarly, imagine the economy as consisting, in part, of a vast array of technologies. Through the appropriate linking or combining of one technology with another, a new technology different from the original components in both form and function comes into existence. Kauffman views this process as occurring within a space in which mutations periodically occur, increasing the diversity of the objects within the space and leading on occasion to new technological species, and at times to extinction. Standard economic theory does not offer an explanation for how this diversity comes about, a weakness that concepts such as recombinant growth appear to remedy. These, we should note, are concepts Weitzman (1998) develops in his seminal paper. We discuss this in more detail below.[2] In addition, Fleming and Sorenson (2006) develop a theory of invention that utilizes the theory of complex adaptive systems. Using patent citation rates, they find that invention is a process of search over "technology landscapes."

Arthur (2009) views technology in a similar manner as discussed above. For him it is, in part, the entire collection of devices and engineering practices available to a culture (Arthur: 28). But it is more than that, for these technologies emerge, mature, die (become obsolescent), and recombine in an autopoietic fashion that adds a whole new dimension to the concept. This is also, as Arthur notes, what the technology thinker Kevin Kelly calls "the technium" (also see Kelly 2010).

One can view the process of innovation as coming about through self-organizing processes within the economy. The economy is an intricate web of interconnections among countless agents in the system; some agents are more connected than others, and some have few or, perhaps occasionally, zero connections. The relationships and interconnections that do exist are characterized by both positive and negative feedback, with the various feedback relationships operating at different levels (some of the feedback loops are confined to near neighbors) while other feedback loops affect a large number of agents. Moreover, the various types of feedback operate at different time scales. The economy can exhibit a wide range of behaviors, ranging from steady growth to decay, sudden collapse, sudden spurts of growth and innovation and creativity, etc., through its self-organizing properties characterized by periodic bursts of self-organized criticality.[3] Thus, that period of time characterized by, for example, the emergence of the Internet, with the array of technologies that "came together" to serve as the technological foundations of this innovation, can be viewed as a period of self-organized criticality, or of rapid, nonlinear, unanticipated change. Similarly, the transition period from steam to electricity, or from vacuum tubes to integrated circuits and its attendant complementary and ancillary technologies, represents a similar set of advances, all of which can be characterized as self-organized or spontaneous processes.

These complex systems, while potentially vulnerable both to exogenous shocks as well as to endogenous disturbances that can damage or, in extreme cases, destroy the system, nevertheless hold the potential, through the creation of webs of interactions of various kinds among actors, to accelerate the process of innovation and creativity in unexpected ways. In this paper (similar to Kauffman and Arthur), we are interested in the most important overarching feature of the economy and society: the growth in diversity of goods and services and the underlying technological advances that make them possible. We observe this growth from the era of pre-humans using primitive tools to the array of technologies that surround us today, from the simple to the enormously complex.

A somewhat better understanding of the process can be found in work by complex systems researchers concerned with the phenomenon of punctuated equilibrium. Patterns of punctuated equilibrium appear to capture the reality of the biosphere, where evolution appears to experience long periods of relative stability and stasis followed by rapid changes, including extinction (see, e.g. Eldredge and Gould 1972). Others (Watts 1999; Newman 1999; Newman and Watts 2003) have found that punctuated equilibria in ecosystems may be related at a deep level to network interconnections. These authors show that networks may organize in ways that have a mix of dense and sparse connections. Jain and Krishna (2002a; 2002b) have found that removal of certain species from simulated ecosystems, while typically not resulting in harm, will occasionally trigger extinction events if these species are highly interconnected with others.

Conversely, at some point in the lifetime of the system some change in the status quo, an innovation (i.e. a mutation), leads to a cascade of other innovations as non-linear positive feedback processes are initiated. A change to an existing technology, the emergence of a new technology resulting from a nonlinear interaction of two or more agents, or emergence of an ensemble of new technologies or innovation, produces massive change in the system. The result is the emergence of an S-curve in technological innovation (e.g. Kuznets 1930; Mansfield 1961). These growth curves are typical of far-from-equilibrium, self-organizing network processes transitioning between two equilibria. The equilibria are periods of high stability and low creativity; the transition stage is a period of low stability and high creativity. Periods of stagnation—be they technological, economic, artistic, etc.—are stable equilibrium states between much more creative far-from-equilibrium states.

Kauffman describes a version of our recombinant growth economy with the metaphor of "Lego world." Think of an economy as consisting of countless Lego parts. These parts can be combined with another part or parts to create new technologies. In principle, the number of combinations approaches infinity. A vast number of combinations may not be viable, but that nevertheless leaves countless other potential innovations. Lego world does not, by itself, provide a recognizable representation of the econosphere, since by itself there is no mechanism for the dying out of certain products and services as new products and services came into being. But this could be easily built into a Lego model, in which certain combinations produce a "toxin" that kills off older combinations that possess inferior technological architectures.[4]

The closest mainstream economics has come to capturing this kind of proto-model of innovation can be found in Weitzman (1998). Curiously, there appears to have been relatively little follow-up by others, which is striking since Weitzman's rigorous analysis provides opportunities to deepen our understanding of knowledge production and ideas, which are integral parts of the innovation process. However, the basic idea goes back to William Ogburn (1922), who said that "the more there is to invent with, the greater will be the number of inventions" (as quoted in Arthur: 172). Weitzman provides at least the beginnings of the micro-foundations of ideas by showing how the production of new ideas is a function of newly reconfigured old ideas. Using the metaphor of an agricultural research station that develops improved plant varieties, he demonstrates how knowledge can build upon itself in a combinatory positive feedback process.

The system described by Weitzman represents a positive feedback system, in which the "signal" is amplified over time. Such systems are in disequilibrium, and have historically been of less interest to most economists than systems that demonstrate equilibrium. However, we are concerned with the way in which economies became complex, self-organizing, adaptive systems, with a particular interest in how such systems evolve in a manner promoting innovation. This means we are interested in both positive and negative feedback processes, as both are in fact at work in any complex process. Of particular interest is how these processes can be accelerated in ways that can advance society's future technology portfolio.

To have self-organization in an action space, one has to have a certain level of density known as interactive density. People cannot be too spread out, as they often are in rural settings, nor too close together, as in a crowded elevator. People have to be close enough together to interact in productive ways. Such conditions are found on large scales in cities, and on smaller scales in places like Starbucks or within organizations. In other words, as Gordon and Ikeda argue (2011: 10), the important kind of density is that which optimizes "the number of informal contacts," or interactive density. Indeed, one of the ways organizations improve coordination is by increasing interactive density among people with the same goals. Without interactive density, self-organization cannot occur in physical, biological, or social processes.

Power law distributions are one of the main features of complex self-organizing systems. We would thus expect a healthy self-organizing economy to have power law distributions of firm sizes and ages, wealth distribution, etc. This comes about precisely because there is freedom of entry and exit and equality of status among actors. For example, Bill Gates has more money than most people. Why? Because he has engaged in more economic exchanges than have most people. If you created a network map of exchanges, Bill Gates would have an extremely large number of edges. Most people would have very few. In fact, we see a power law distribution, with few people having a large number of edges, somewhat more people having a medium number of edges, and a large number of people having few edges. We see this same thing happening in science, where there are a few highly-read scientific "stars," and a large number of people publishing scientific papers that may never be read by anyone other than the peer reviewers and journal editor. Further, there are rules that facilitate these elements and which facilitate interactions such that there is increased cooperation. All of these contribute to the creation of power law distributions. An economy without power law distributions of the appropriate elements would not be as wealth-maximizing as one that did have power law distributions, much as a scientific order without power law distributions of the appropriate elements would not be as able to maximize scientific knowledge creation as one that did.

Similarly, technological innovation takes places in a spontaneous order action space. All potential technology is in what Stuart Kauffman calls the "adjacent possible," an action space which includes all of the technology that can be invented from the technology that has been invented, but which includes both those technologies that will not ever be actualized as well as those that will be actualized (Kauffman 2000: 142-144). It also includes a wide range of innovations, from changes that matter very little to major changes that transform the world (e.g., the airplane). We should not be surprised to find that the kinds of innovations which take place also follow a power law distribution.

As mentioned above, most economists consider technology to be an exogenous shock to the economy, throwing it out of equilibrium. This makes sense if the economy is only the catallaxy. But if "the economy" is a combination of a variety of spontaneous orders, including the catallaxy, money and finance, and technological innovation, and if we consider the fact that most economic growth comes out of upstart businesses (typically started because of some kind of innovation), then it makes little sense to consider technological innovation as exogenous. Instead, we side with Schumpeter's view of technological innovation as endogenous to the market economy, meaning the market economy is in a constant state of flux due to new technologies causing older technologies—and the businesses producing them—to go extinct (or, in the case of businesses, to change or go extinct). This being the case, it is vital to understand technological innovation as an independent spontaneous order as well as its interactions with the catallaxy to co-form the market economy.

What about the Internet? The Internet should be understood as a new kind of self-organizing social network that increases social coordination over space and time, shrinking space and time. It thus increases interactive density on a truly global scale (see, e.g., Varian 2010). Varian begins by pointing out the combinatorial characters of the Internet. Perhaps the only difference between the Internet and earlier examples of combinatorial innovation, or waves of such innovation, is that so much that is today associated with the Internet technology space has come into existence in just a few years. Varian believes this is due to the fact that the ultimate essence of the Internet is the technologies that undergird it, such as programming languages, protocols, standards and the like.

Still, the kind of combinatorial creativity embodied in the Internet is not that different in certain respects from some earlier technologies. The construction of the jet engine was a marvelous engineering feat. But the jet engine was not built tabula rasa. It represented the bringing together of countless technologies such as advanced metallurgy, axial flow compressors that represented a substantial advance over radial-flow compressors, sensor technology, and the like. Further, technology creates opportunities to create new technology. While the jet engine emerged from combining and recombining many technologies, its invention in turn led to the improvement of those technologies that gave rise to it in the first place. The very fact that a jet engine exists creates the opportunity (or need) for still greater advances in metallurgy, compression systems, and so forth if jet engine technology is to advance. Arthur says, "many of a technology's parts are shared by other technologies, so a great deal of development happens automatically as components improve in other uses "outside" that technology … a technology piggybacks on the external development of its components" (Arthur: 134). Another example is the development of the radio transmitter. As related by Arthur, engineers were able in 1911 and 1912 to combine the already existing triode with other components to create an amplifier. The amplifier circuit, combined with coils, capacitors, and resistors produced an oscillator, a circuit that could generate a pure single-frequency radio wave (Arthur: 168-169).

We do not need to limit ourselves to purely "physical" technologies. The creation of the financial derivatives market could only occur as a result of a combination of ideas that relied upon computers: the creation of the Black-Sholes equation for valuing the future price of an option and software capable of computing sometimes enormously complex mixing structures, and other advanced information technologies. Without the presence of those phenomena, modern finance would not exist.

While our above discussion—with the possible exception of the Internet—gives examples of particular technologies, we can think of entire clusters of technologies that interact together. The development of the railroads in the 1870s—itself the result of innovations in steel making—led to a whole array of new industries, products, and skills, all of which intersected with each other. Thus, the originating railroad technology created an entire technology space. The creation of the biotechnology industry led to the creation of a similar technological ecology from the 1990s to the present day. Fuchs (2003) makes this point in regards to the Internet. His essay is in many respects rather conservative; he views the Internet as human actors acting within the technological structures provided by the Internet to produce new informative content (in our language, innovations). The technology and human actors combine to create a socio-technological system that reproduces communicative actions "in [themselves] produced and reproduced by communicative actions" (Fuchs (2003: 1).

Subbarao takes a more expansive view of the Internet as a self-organized system (or, in our language, spontaneous order). He states that "even though the Internet encapsulates a world of its own … it coexists with the rest of the universe … as the Internet evolves and adapts the environment it resides in changes causing a cycle of adaptation." The Internet coevolves with human society through feedback loops, both positive and negative, resulting in further iterations of the original system, in a never-ending process of co-evolution, iteration, and feedback, all inseparable from each other.

A variety of Internet institutions—such as Facebook, Twitter, and various blogs—allow for increased coordination, facilitating this phenomenon. All the other spontaneous orders overlap the Internet, though none overwhelm it. Over the years, there has been limited success at monetizing the most popular online institutions precisely because the Internet is not identical with the catallaxy. It is its own order. Governments' efforts to control the Internet have met with the same kind of limited success, as we see when it tried to control the catallaxy (where control creates black markets) and the artistic orders (where censorship simply drives works underground and make them more attractive). The Internet, like globalization, also allows people to physically move to new locations while continuing to provide the same services to the same people if any particular government becomes too strict.

The recombinant character of the Internet was easier to realize because it was inherently a communications technology, the essence of which is information in the form of computer code, a point made earlier by Varian (2010). Other technologies demonstrate recombinant capabilities, such as the integrated circuit technologies of the 1960s and 1970s, but these were physical objects that could not necessarily always be developed everywhere in the world simultaneously.

The Internet not only possesses characteristics that allow it to be easily "innovated," modified, and even recombined, but as a transmission device, indeed an extremely effective one, it makes other innovations of a recombinatorial nature possible through its ability to transmit information to, in principle, everyone on the planet. While most social orders are "virtual," in the sense that we are not literally connected in our networks, but only mentally connected, the Internet is both physical and virtual. It is literally, physically, a network. And, like all other spontaneous orders, it is capable of computation. It is thus a technological-social network—a literal cyborg order. We are not physically connected to it yet, but the Internet is very much a human-machine interface. In other words, it is a physical-virtual spontaneous order. And this facilitates the way we interact with others through it. We think there is little question we interact with others online differently than we do in person. As with anything, there are costs and benefits—one benefit being one can find like-minded people more easily for collaboration.

Interacting Orders. As already observed, when one talks about "the economy," rarely is one talking exclusively about the catallaxy. For example, if it is true that most new jobs are created by startups, and if most startups are started by innovators with a new product, way of doing things, etc., then it will be difficult to understand labor economics without understanding the technological order, out of which these innovations come. We need to understand the interactions between the technological order and the catallaxy if we are going to understand the economy as a whole.

If we assume a catallaxy at equilibrium, in which actions are fully coordinated, what is it we are actually assuming? We are assuming the same actors are always involved (stable population), the institutions are stable (will not change over time, at least for the duration of the analysis), and that technology does not change. In a dynamic form, this is what Mises (1949/1966) called the "evenly rotating economy." In other words, we must remember that static equilibrium analysis "does not deal with the social process at all and that it is no more than a useful preliminary to the study of the main problem," which is how economic coordination takes place (Hayek 1945: 91). You start there in order to add elements piece by piece to see what happens as it becomes more complex. What happens when we add complexity in the form of a new technology? As Hayek observes:

Since equilibrium relations exist between the successive actions of a person only insofar as they are part of the execution of the same plan, any change in the relevant knowledge of the person, that is, any change which leads him to alter his plan, disrupts the equilibrium relation between his actions taken before and those taken after the change in his knowledge. In other words, the equilibrium relationship comprises only his actions during the period in which his anticipations prove correct. ("Economics and Knowledge" 36)

In other words, any new information is disequlibrating. And since one must also coordinate one's actions with others, this means only if people act as expected will the system reach equilibrium (Hayek, 38). But "the equilibrium connections will be severed if any person changes his plans, either because his tastes change . . . or because new facts become known to him" (52). Technology has a similar effect.

For example, if we assume an economy in which all overseas travel is done by boat, what will happen when airplanes are invented that can carry large numbers of passengers overseas faster? In broad terms, the equilibrium economy will be thrown out of equilibrium. Coordinated plans will become, as Hayek (1945) and Lachmann (1986) argued, discoordinated. For a while, the entire system will be in a far-from-equilibrium state—whereby the system in question is in an elevated state of complexity and creativity. People traveling from the U.S. to Europe for business would be able to plan not to meet with their potential business partners in a week, but the next day. Initial air travel would be expensive, meaning those with more time than money would still travel by boat while those with more money than time would travel by plane. This is going to affect who does what business, the speed at which that business gets done, etc. Further, insofar as business success is often time-dependent, those who can travel fastest would be able to engage in more successful business ventures.

What we described above is a punctuated equilibrium, a concept touched on earlier. A change causes the system to jump from one equilibrium state to another. The transition is a far-from-equilibrium state—plans are discoordinated, new plans are created, people try to coordinate the new plans, etc. In the example above, new business opportunities become possible because, with the introduction of a single new technology, travel time has decreased for certain people. And to create the new product, employees are needed to build the planes, etc., which would affect the labor market and, thus, the price of labor, etc. As Camplin (2009: 70) observes, "The invention of the car caused an intricate system to form around them. And we, the creator of the car, are the main components of that system." New technologies emerge to facilitate the creation and use of the new technology, further disrupting the catallaxy and creating new opportunities for economic growth and wealth-production. And this is for just one new form of technology. However, in the real world, new technologies are being constantly introduced. Thus, the catallaxy is always in a constant far-from-equilibrium state. Plans are always transitioning from coordinated to discoordinated, and back again. As a result, we are never acting in equilibrium; rather, the constant influx creates an economy in constant flow, properly understood as a process.

Even if there is a certain degree to which we can understand the catallaxy as a system that can at least potentially reach equilibrium, almost by definition the technological order cannot be similarly understood. The technological order is in a constant state of change, since innovation is its primary feature. It thus closely resembles the scientific order, which cannot exist without the constant creation of new knowledge. Both technological innovation and knowledge creation can speed up or slow down, but if it stops, by definition the order no longer exists. Since new technology or knowledge is what drives the creation of the next round of new technology or knowledge, then each of these orders must necessarily always be changing. Each must thus remain in a far-from-equilibrium state. Given that technological innovation (in new products, more efficient ways of doing things, etc.) is the cause of economic growth (creating new products, jobs, businesses, etc.), the true origin of wealth is the emergence of the symbiotic technological-catallactic order. In other words, it is no mere coincidence that there was a sudden creation of wealth in the West at the same time the technological order emerged (which also stimulated the emergence of what Randall Collins terms "rapid-discovery science").[5] Thus, to understand the economy, one has to understand technological innovation.

What we are identifying is the emergence of what Collins terms "a kind of cyborg network." There had always been technology and, as such, a technological spontaneous order. And there had always been trade and, thus, a catallactic order. But the interaction of the two drives wealth creation. Technological innovation drove the rapid expansion of the catallaxy; thus, economic growth boomed. Each symbiotically co-creates the other, and drives further growth.

We can thus see that technology and the market economy are intimately tied together, although perhaps not as many think. They are co-evolutionary, co-creating spontaneous orders. These symbiotic orders are able to create such explosive growth precisely because the constant influx of new technology keeps the catallaxy in a far-from-equilibrium, and thus in a constantly creative, constantly changing, constantly growing state. It is technological innovation which drives economic growth (and the growth of scientific knowledge) and not the other way around. To understand economic growth, we have to understand the nature of technological innovation.

Generating Innovation in the Technological Space

Ultimately, innovation occurs when one has the ability to identify what innovations, when combined with other innovations, produce something new. If we combine A and B, we get C, and C has properties possessed by neither A nor B. Note that A or B, or both, do not have to be physical objects; they can be ideas, or they can be protocols or software that take on purely electronic, or even symbolic, form. The next step is to offer a mechanism for accelerating that growth and innovation within the technosphere. That mechanism, as we have said earlier, is CAS, or the principle of spontaneous order. One first needs to think of the entire set of technological possibilities, both as it exists and the set's near infinite potentialities, as a CAS. What computation does is not only explore all the possible interconnections that might exist between the components of the system in order to determine what interconnections yield the greatest potential, but to serve, endogenously, to generate accelerated interconnections between different components of the system in a way that pushes different regions of the system toward self-organized criticality (SOC), or punctuations in the system characterized by technological revolutions. The aim is to consciously create computational means that accelerate the pace of technological evolution (increased frequency) as well as generating increased amplitude (deeper and more profound advances). This can include genetic algorithms, artificial neural nets (ANNs), and other algorithmic processes in various interactions with each other, databases, and human innovators, which can all be interconnected.

Advanced computation allows for advances in technology that in turn can be subjected to computational analysis, which in principle could proceed indefinitely. At its most fundamental level, computation allows for an assessment of all potential elements of the economy, and using extensive databases of all existing technologies combined with powerful genetic algorithms, ANNs, etc., could result in the development of extremely powerful forecasting tools that generate varying probabilities of success for different technologies. Of course, much of the object space within the technosphere will be non-productive, i.e., it will not yield fruitful innovations. But the computational systems will learn from mistakes and become steadily more efficient in "finding" productive innovations.[6]

The idea that computational power can be used to develop technological innovations is not a radical idea. The computational ability to allow completely computerized labs to perform experiments autonomous from human researchers already exists. Not only can such high technology laboratories perform experiments, they can develop hypotheses to test, devise (not just perform) experiments, take the results, and develop revised hypotheses, using what could be called classic Popperian logic. Such tools are already in use in pharmaceutical laboratories, and have the potential to substantially increase such facilities' efficiency. It is true the software for such programs is human-designed, but that does not mean such programs need to be completely deterministic. Moreover, software itself can be designed to evolve through the application of genetic algorithms. Indeed, the growth of fuzzy logic systems allows for the incorporation of at least some degree of pseudo-autonomy into these automated systems. Future advances in hardware and fuzzy logic software should magnify the capabilities of such laboratories many times over (Dickerson and Kosko 1994; Kosko 1994).

The activities of automated pharmaceutical labs is no different from our earlier point that advanced computational resources can be directed toward the evolution of objects in the technosphere, and that one or more of those objects can be linked to form new technology. The term "objects" as used here includes objects that exist at the molecular or even atomic level. This is where nanoscale chemistry and, ultimately, nanotechnology comes into play. Given the number of potential combinations of "objects" available, the number of new technologies becomes effectively infinite.

Moreover, technology may include software and protocols that can be altered, modified, rewritten, and combined with other programs. Computational advances can also provide for a means of sifting and culling large databases that currently exist, or will exist, in biology, biochemistry, organic chemistry, physical chemistry, and hundreds of other specialized areas of advanced research, including engineering and computer science. The problem researchers face is that cutting-edge research in these fields tends to be so specialized that they are often not readily accessible to researchers in other disciplinary areas. Interdisciplinary researchers and scholars will be needed to build the bridges needed to keep technological innovation accelerating.

Advanced computation is not limited to the nuts and bolts of experimental research. In recent years, hardware and software have been developed to the point that computers can formulate formal proofs of mathematical theorems. Some of these theorems are sufficiently complicated and intractable that human mathematicians would have great difficulty solving them. There is every reason to think future computational capabilities will allow for other capabilities, including the creation of theorems. Such theorems and proofs, particularly in areas of applied mathematics, may have enormously important implications for technological advance. These efforts go back to at least the 1970s, beginning with the Boyer-Moore theorem prover $N_q$thm. Some systems today can produce proofs hundreds of steps long with little intervention by the programmer (Wolfram 2002:1158).

The development of innovative systems that expand the technological space does not need to be restricted to artificial intelligences. The transmission of information to anyone interested—a potential seven billion individuals—provides substantial opportunities for human-AI interfaces that will dramatically expand the capacity for innovation. We will be able to achieve—through AI interfacing with the collective intelligence motivated by the Internet and its successors—a degree of innovation not possible in the past. It is easy to imagine a "technology innovation space" online, where ANNs are used and are being designed and evolved to aid in technological innovation. The designs of every technology ever invented can, in theory, be stored in a database and downloaded into an ANN or a set of ANNs for the purpose of innovation. ANNs store data conceptually rather than perfectly, allowing for more complex recombinations. Humans can submit their own innovations, feed data into the ANNs, propose modifications, and select new technologies to test. With the continuing development of 3-D printers, individuals will be able to create models—or even complete objects—from the blueprints created online. 3-D printers will individuate testing more, allowing many to test and bring their ideas and insights back online to improve the designs (Chua et al. 2003; Wittbrodt et al. 2013). Those advances may well be promoted or advanced by highly sophisticated "prediction markets" in technological innovation that will direct financial resources toward the most promising array of choices (Bell 2006; Wolfers and Zitzewitz 2004).

It was described earlier how software can evolve and adapt. It is also possible for physical objects to replicate, along with software. The age of nanotechnology offers opportunities for promoting accelerated technological advances. The principle of self-replication plays an important role in nanotechnology, where it is believed that nanomachines would be capable of engaging in self-replication using material from the surrounding environment. Such nanomachines could be used for any number of tasks, from construction to intelligence activities. Examples of the concept of self-replication are macro-molecular Von Neumann machines. Von Neumann demonstrates that such technologies are possible in principle (von Neumann 1966). What we suggest are that such devices would be capable not only of replication, but self-improvement, advancing the technological parameters in highly accelerated fashion. The capability of millions of such machines to engage in self-evolution with different machines dedicated to the different aspects of the technological space, yet sharing distributed intelligence, offers real opportunities for technological advance.

The Theory of Computational Equivalence

Lipson (Zagal and Lipson 2009; Kim and Lipson 2009), who has been a leader in the development of machine intelligence, believes machines can discover scientific laws in an algorithmic fashion, self-reflective robotic systems can be devised, and machines are capable of formulating and testing scientific hypotheses; moreover, his work suggests the possibility of machines being able to develop other machines, and machines building other machines, consistent with the Von Neumann principles of self-replication. It should be possible, in principle, for such machine intelligence to not merely replicate, but to innovate. Machines can create other machines; but through the use of advanced genetic algorithms, they can build machines that are improvements upon the original.

The ability to create new technologies may be advanced by Wolfram's (2002) formulation of the principle of Computational Equivalence. Some of his most important work has been devoted to the theory and application of cellular automata. Cellular automata are cells on a grid of 2, 3, or even n dimensions, with each cell representing a particular value, typically 1 or 0 (but not necessarily limited to these binary choices). The cells behave according to simple rules involving the values of adjacent cells, the value of the cell at (-1), and so forth. These cells are, in principle, capable of sophisticated computing. Indeed, automata have the ability to act as a universal Turing machine, a mathematical abstraction formulated by Alan Turing in the 1930s. Such a machine would be able, in principle, to perform any computation. Automata, as shown by Wolfram, may be able to do the same thing.

But this is only part of the story, and it does not capture the full notion of computational equivalence, the implications of which are potentially staggering. The Computational Equivalence Principle states that all processes, whether produced by human effort or that occur spontaneously in nature, are computations (Wolfram: 715). Human-made computers engage in computation, and so do brains. But so to do a vast array of seemingly simple systems that appear in nature. There may be a near-infinite number of natural computers and protocols existing in nature that can be altered, modified, rewritten, and combined with other programs (Wolfram: 716).

This concept of the "universe as computer" is not unique to Wolfram. The cosmologist and theoretical physicist Seth Lloyd has proposed something similar. For Lloyd (2006), the answer to the question "what does the universe do?" is "it computes." Every single particle in the universe is energized in the act of computing its current and, indeed, future states. When the principle of universal computation as captured by the concept of cellular automata is married to the principle of computational equivalence among an array of other systems, biological and otherwise, the implications for technology appears to be highly promising.

Engineering, Wolfram notes, has in certain deep respects been hindered by the need for methodologies based on setting up systems whose behavior is sufficiently simple that every aspect can predicted, as doing so excludes many systems. Yet, it is possible to set up systems based on simple rules that can exhibit highly complex, but possibly unpredictable, behavior. Thus, we have the ability to develop technologies better able to emulate "natural" technologies. This means that once the principle of universal computation is better understood, this area of the technosphere previously inaccessible to us will be opened up (Wolfram: 840).

We have offered a means by which the pace of technological change could be accelerated. If that could be accomplished, the technological horizons of what a future technological civilization might be able to accomplish are potentially impressive. If the behavior of complex systems teaches us anything, it should be that (a) seemingly stable equilibrium systems can become non-equilibrium in a very rapid manner, (b) these systems are subject to positive feedback, and (c) processes of self-organization resulting from seemingly unconnected, separate technological ideas and beliefs can generate a self-organized criticality that advances a system to a whole new level. Thus it would not be surprising to see such a process unfold over the next several decades.

Many technologies, or clusters of technologies, may serve as catalyst for a radical shift in technological capabilities. Moreover, the abilities those technologies offer us, such as the ability to explore and utilize space in ways heretofore impossible, may create a renewed burst of innovation and entrepreneurialism that will feed back into other advances in ways that are as yet unclear, creating even more rapid advances.

Conclusion

This essay has sought to demonstrate the interconnectedness between technological innovation and the catallaxy, the characteristics of complex adaptive systems, and how self-ordering systems of innovation could be developed that would accelerate the process of technological advance. The inspiration for this study comes from Kauffman (1993, 2000), who has contended that what has been lacking in economics is a theory of innovation.

We suggest that innovation takes place within the framework of a complex, self-organizing system possessing the potential for self-organized criticality. Thus, what we have suggested here is a way of thinking about accelerating the self-organizing criticality features of the system. Indeed, the economy needs technological innovation; but equally, technology needs the economy. As Boettke observes in *Living Economics*, technological knowledge is

> transformed into useful knowledge through the ordinary business of commerce. Without the guiding role of property, prices and profit/loss accounting, the gains from innovation would not be realized. The reason for this is simple—without the guiding signals and incentives of the price system, economic actors cannot sort out from the array of technologically feasible projects those that are most economical to pursue. And absent that economic knowledge, technological ventures will be plagued by a systemic waste of resources (Boettke 2012: 384).

Each keeps the other creative, innovative, and more efficient.

Arthur (2009) perhaps comes closest to describing the dynamics of technological innovation. We have reached a stage of technical development where the "collective of technology" (Arthur 2009: 170), or the technosphere, is self-reproducing, or autopoietic. Novel technologies are created from existing technologies and all future technologies will derive from what now exists, but in some completely unexpected way. In other words, we have the potential for constant feedback, whereby innovation begets innovation. This is not meant to seem like some mystical process. To use Arthur's language (Arthur, 169), it does not imply that technology has consciousness, but that "the collective of technology builds upon itself from itself with the agency of human inventors and developers much as a coral reef builds itself from itself from the activities of small organisms." Perhaps innovation has always, in this sense, been autopoietic. Only today are technologies available to vastly expand the pace and quality of innovation. As a result, the technosphere may one day soon move away from being the result of human action and instead become a result of technological action.

We will likely see the creation of artificial intelligences greater than human intelligence, capable of autonomous thought, and capable of independently making further advances in the fields of nanotechnology and genetic engineering. In the end, it is advances in computation, the end result being AI, integrated with advances in nanotechnologies and genetic engineering, that can produce a world of new possibilities, wealth, and prosperity.

Notes

[1] Division of Liberal Arts and Life Sciences, University of North Texas at Dallas and School of Economic, Political and Policy Sciences, University of Texas at Dallas, respectively.

[2] Kauffman criticizes standard economic theory as lacking insight into this area (Kauffman 212-218). He points out that the secular increase in diversity of goods and services over millennia is not explained by competitive general equilibrium, which is the computational framework for understanding how prices clear. But, such a framework depends on complete markets, and since it assumes one can "finitely" prestate possible dated contingent goods, Competitive General Equilibrium (CGE) is limited in its usefulness. It is not possible, in other words, to finitely prestate all possible goods and services. We simply cannot know the possible outcome or, to return to the language of choice here, the possible combinations that may result that produce new goods and services, i.e. the phenomenon of recombinant growth. None of this is to deny the great contribution that Kenneth Arrow and Gerard Debreu made in formulating their fixed point theorem for CGE, which provides an explanation for the clearing of markets in a competitive economy. We merely point out that it cannot explain certain real world phenomena.

[3] This analysis is not at all dissimilar from one of Friedrich Von Hayek's most important contributions to the field of economics and, more generally, moral philosophy, in the concept of catallaxy. Catallaxy is Hayek's term for the spontaneous order that is created as a result of exchange and specialization. The term, catallaxy, the study of which is known by the term catallactics, is a catalyst in the creation of new products, innovations and ideas. It is through the ongoing and perpetual act of catallaxy that the necessary signals are disseminated through the economy and shape the countless decisions that are made. Catallactics can be thought of as a self-organizing process that drives the creation of more and more advanced technologies over time. We propose here ways in which such self-organizing systems can be designed to accelerate the process of technological advance.

[4] The alternative approach to the Lego economy is a grammar model. We leave the details to Kauffman (2000), but Kauffman provides an outline of a mathematical analogue of the Lego economy. That model uses binary symbol strings representing goods and services. The grammar specifies how different symbol strings interact with each other, to produce new symbol strings. Grammars can be both "content insensitive" or "content sensitive," in which case the latter grammar takes account of the context surrounding the symbol string interaction.

[5] Collins argues that modern science is "a distinctive form of social organization which I shall call rapid-discovery science," which emerged as a new network alongside that of philosophy (his primary focus in his The Sociology of Philosophies). He argues that rapid-discovery science is actually two networks, "one of scientific and mathematical researchers, and in symbiosis with it a second network comprising genealogies of machines and techniques which generated an ongoing stream of new phenomena for scientific research" (382). Indeed, the laws of thermodynamics were discovered because of the invention of the steam engine, not the other way around.

[6] It is also well known that computers have become increasingly successful at defeating humans in a variety of games that require skill. At the time this manuscript was being prepared, an astounding display of computational virtuosity was on display when the IBM supercomputer Watson defeated two of the top human players of the game show Jeopardy. For fans of AI, this performance was in many respects even more impressive since it required the computer to understand often subtle contexts in which a word is used. As the ability of computers to respond to increasingly less structured and deterministic ontology expands, the day will surely draw closer when a computer will be able to pass the Turing test, in which a human would be unable to distinguish a computer's responses from another human.

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