Title: **On the emergence of ecological and economic niches**

Authors: Roberto Cazzolla Gatti[1,2*], Roger Koppl[3*], Brian Fath[4,5,6], Stuart Kauffman[7], Wim Hordijk[8], Robert Ulanowicz[9,10]

Affiliations:

[1] Biological Institute, Tomsk State University, Russia

[2] Konrad Lorenz Institute, Klosterneuburg, Austria

[3] Syracuse University, USA

[4] Department of Biological Sciences, Towson University, Towson, MD, USA

[5] Advanced Systems Analysis Program, International Institute for Applied Systems Analysis, Laxenburg, Austria

[6] Department of Environmental Studies, Masaryk University, Brno, Czech Republic

[7] Institute for Systems Biology, Seattle, Washington, USA

[8] SmartAnalytiX, Vienna, Austria

[9] Department of Biology, University of Florida, USA

[10] Center for Environmental Science, University of Maryland, USA

* corresponding authors' email: robertocgatti@gmail.com and rkoppl@syr.edu

Abstract

The origin of economic niches, conceived as potential markets, has been mostly neglected in economic theory. Ecological niches emerge as new species evolve and fit into a web of interactions, and the more species come into existence, the more (exponentially or power-law distributed) ecological niches emerge. In parallel fashion, economic niches emerge with new goods, and niche formation in economics is also exponentially or power-law distributed. In economics and ecology alike, autocatalytic processes drive the system to greater and greater diversity. Novelty begets novelty in a positive feedback loop. An autocatalytic set of self-enabling transactions feed back upon one another in combinatoric fashion to generate progressive diversity. While these combinatorial dynamics cannot be prestated, the model explains the "hockey-stick of economic growth" – a pattern of prolonged stasis followed by a sudden takeoff, such as occurred during the industrial revolution or the Cambrian explosion in ecology. Several implications derive from our niche emergence model, including the idea that the evolutionary process of technological change is not something we do; rather, it happens to us.

Introduction

We develop a model of the emergence of "economic niches" in which niches multiply and ramify over time. Consider mouse pads. There was no latent market for mouse pads in 1870 or in 1970. Any attempt to sell "mouse pads" would surely have failed. No one had a use for them. There was no latent demand. Once personal computers with graphical interface software began to be sold to ordinary households, however, an economic niche for mouse pads opened up. There opened a latent market, which became actual and overt once suppliers began to offer them. Once the public had computer mouses, it could instantly understand what a "mouse pad" is and why a person might want one. The economic niche opened when the first computer mouse was sold. Presumably, however, it was only some time after the niche opened that an "alert entrepreneur" (Kirzner 1973) first noticed the opportunity and acted on it.

Our theory of niche evolution helps to fill a gap in the economics literature. In our theory, economic goods and relations, like species in an ecosystem (Cazzolla Gatti 2011), grow increasingly diverse and complex over time. This ramifying complexity is a central feature of economic life, and yet it is largely absent from the dominant models of modern economics. Following Mandeville (1729), Smith (1776), Menger (1871), A. A. Young (1928), Beinhocker (2007), Arthur (2009), and others, we recognize that economic growth entails an increase in the variety of goods produced, which Koppl et al. (2015) call "cambiodiversity". But, just as new species need new biological niches, new goods require new economic niches. There must be a latent market, i.e., a new economic niche for the good to enter, which arises out of a larger economic system. If there is, then the entering good transforms the latent market into an active market. There must first be the niche, the latent market. Then the good can enter. Our theory of the evolution of economic niches explains how they emerge and ramify over time as technology evolves.

Our theory generalizes our mouse pad example. It follows from the parallel emergence of ecological niches recently proposed by Cazzolla Gatti et al. (2018). An economic niche might be called a "latent market." For our purposes here, a market is just an ongoing set of exchanges. These exchanges might be supported by various physical structures, social habits, legal institutions, and so on. As Hodgson (2007, p. 326) notes, "markets involve social norms and customs, instituted exchange relations, and information networks that have to be explained." We endorse the view that the institutional enablers of economic exchange require (evolutionary) explanation. Our current focus on niche emergence in the evolution of the technosphere, however, seems to allow us to leave all such enabling institutions in the background for the time being.

In this paper, we are focusing on the evolution of the technosphere and how that evolution creates a ramifying process of niche creation. Thus, we ignore the possibility that some desirable good becomes technologically possible but cannot find a market because of "institutional" factors such as weak property rights. Such possibilities are quite real. Weak property rights in medieval China, for example, seem to have thwarted innovation (Lowery and Baumol 2013). Our model of niche evolution assumes a favorable institutional environment only as a first approximation. Our comments in the discussion section on the long-run endogeneity of institutions may help to justify this approximation. It remains, however, an approximation that should be dropped when it is convenient to do so.

Thus, again, in this paper a "market" is just a set of exchanges. An economic niche is a potential or latent market. It is a market that could be created if a potential seller would only offer the relevant product. In our theory, each new good creates new economic niches and, therefore, new possibilities for more innovative goods. Some of those possibilities are realized, thereby creating yet more niches for yet more goods. In this way the number and variety of economic niches grow over time.

Our vision of ramifying economic development may be similar to that of Jane Jacobs. In *The Nature of Economies,* she wrote, "development without co-development webs is as impossible for an economy as it is for biological development" (Jacobs 2000). W. Brian Arthur (2009), in his *The*

Nature of Technology, has stressed the role of cumulative new combinations of existing technologies as a basic mechanism in the open-ended evolution of the economy, and the roles these processes play in the emergence of ever new economic niches.

Kauffman (1988, 2008, 2016, 2019) has discussed the autocatalytic evolution of economic webs of what we might call “competing” and “completing” goods. Two goods are “competing” if the output of the one tends to reduce the output of the other. They are “completing” if the output of the one tends to increase the output of the other. (This distinction bears an obvious similarity to that between “complements” and “substitutes,” but is not quite the same. We steal our lingo, but not the concept from earlier economists.) Competing and completing goods continually create new economic niches for one another as new goods are formed through new combinations.

Our model is distinct from models of “endogenous product variety.” In these models, which trace back to Dixit and Stiglitz (1977), product variety is ensured by the assumption of imperfect competition, wherein each firm’s individual demand curve is less than perfectly elastic. Such imperfect elasticity is chalked up to differences in the offerings of each firm. A gas station on the northwest corner of a busy intersection will be more convenient for some drivers than an otherwise similar gas station on the southeast corner of the same intersection. Thus, their products are heterogenous. There is “product variety.” Matsuyama (1995) is a good introduction to this literature. (See also, e.g., Venables and Smith (1986), Driffill and van der Ploeg (1993), Weitzman (1994), Bilbiie et al. (2008), Ulanowicz (2009), Lietaer (2010), Kiss and Kiss (2018), Bilbiie et al. (2019), Panyam et al. (2019), and Dave and Layton (2019).)

Precisely because the models in this literature rely on the assumption of “imperfect” (Robinson 1933) or “monopolistic” (Chamberlin 1933) competition, they are equilibrium models and not evolutionary models. Importantly, they generally use the evaluative criterion of “efficiency.” Ecological systems generally exhibit seemingly “inefficient” properties such as “degeneracy” (Edelman and Gally 2001) which Koppl (2018) relabels “synecological redundancy.” Such “inefficient” characteristics create generally desirable properties such as robustness and resilience (Albert, Jeong and Barabasi 2000, Solé et al. 2003). Nor do models of “endogenous product variety” allow for novelty, a central feature or our approach. Although they do have a variable (such as number of entrants) corresponding to “product variety,” the variety of goods does not *ramify* over time. Thus, the concept of niche emergence is alien to this family of models. Nor, finally, do the product differences in these models have any clear or necessary relationship to technological change, as our gas-station example illustrates. Our model of niche emergence, however, is at the same time a model of technological change.

New goods spawn new economic niches, which lead to more goods and more new niches. Over time, the number and variety of goods and the number and variety of economic niches grow. This is not to deny, however, that unfilled niches may fall away over time. In the past, we may imagine, there was an economic niche for an innovative buggy whip made of birch bark. No one filled the niche, however, and today there is no latent demand for birch-bark buggy whips. Although some niches fall away, increasing cambiodiversity entails increasing numbers and varieties of economic niches.

Just as biological species exist in autocatalytic ecosystems (Cazzolla Gatti et al. 2017), market goods exist in autocatalytic economic systems. If a new good is to be successful, if it is to add value to the system, it must be sold on a market. In other words, it must occupy an economic niche. Our notion of “niche” is similar or identical to Brian Arthur’s notion of “opportunity niche,” and his examples are illuminating (2009 pp. 174-176). Arthur makes our central point that new niches lead to new goods that lead to further new niches. He speaks of “technologies creating opportunity niches that call forth technologies.” He says, “Opportunity niches change as the collective technology changes; and they elaborate and grow in numbers as the collective grows.” Arthur provides important theoretical insights without attempting a formal model of niche creation, which we provide in this paper.

A variety of goods may be sold in a given market, as when apple pie and peach cobbler compete for dessert customers. And, a given good may be sold in multiple markets, as when apple pies are sold in both London and Berlin. But the great increases in cambiodiversity that we have seen on all time scales since the arrival of “composite tools” perhaps 300,000 years ago (Ambrose 2001), required the emergence of new economic niches just as the Cambrian diversity explosion of biological species (Conway 2006) necessitated the emergence of new ecological niches. In our earlier example, there must be a niche for mouse pads before mouse pads can succeed in the economy. A theory of increasing cambiodiversity, therefore, seems to require a theory of the evolution of economic niches that would be similar to that of ecological niches (Cazzolla Gatti et al. 2018) or even, perhaps, formally identical to it.

Our humble example of the mouse pad suggests the core insight we stated earlier: New goods create new economic niches, some of which are filled by further new goods, thus creating further new niches. We attempt to give this insight solid analytical foundations drawing on models of niche emergence in ecology. Thus, while we address ourselves to the economics profession at large, our model is also a contribution to evolutionary economics (see e.g., Law 1705, Mandeville 1729, Smith 1776, Veblen 1898, A. A. Young 1928, Schumpeter 1934, Hodgson and Knudsen 2010). Our model of niche emergence reveals a sense in which cooperation is an inherent feature of biological and market competition.

Unsurprisingly, earlier writers have anticipated our views in varying degrees, as we discuss below. But our model of niche evolution contains novel elements and suggests a view of competition and cooperation in market processes that is not widely appreciated today. Past statements of the broadly cooperative nature of “market competition” do not seem to have expressed the precise position we try to map out later in this paper.

Review of the economics literature

There has been a more or less uninterrupted “crisis in economic theory” since at least 1938 when Maurice Dobb (1938 p. 328) spoke of such a crisis in the context of the Great Depression. In 1964, Richard Pasternak declared unemployment to be a “crisis in economic theory”. After dipping her quill in acid, Robinson wrote in 1972 to disparage the “throng of superfluous economists”, who could explain neither unemployment, the first crisis of economic theory, nor the distribution of income, the second crisis of economic theory. In 1974 William Frazer declared the limited role of expectation in standard monetary theory to be a “crisis in economic theory”. In 1979, Jon Wisman spoke of “a widening consensus that the discipline of economic science is itself in a state of crisis” (p. 19). In 1980, the journal *The Public Interest* published a special edition on “The Crisis in Economic Theory”, which included contributions from both leaders of mainstream economics and important heterodox economists (Kristal and Bell 1980). In 1996, The New Yorker published an article on “The Decline of Economics” (Cassidy 1996). David Laibman identified the “doghouse cycle” propelling the unending crisis in economics. “The pattern has been clear: whenever the capitalist economy takes a dive, economists are sent to the doghouse - not for having been unable to prevent the crisis, but for having been unable to foresee it or say anything useful about what to do” (p. 154). In 2003, the “crisis in economics” led to calls for “post-autistic economics”, in which the people in the economists’ models would be more, well, human (Fullbrook 2003). (We note in passing that use of the dehumanizing label “post-autistic” is offensive and inappropriate to purpose). And, in 2016, Keven Hoover said, “The Great Recession of 2007–09 and the related financial crisis stimulated impassioned cries for a deep conceptual reform of economics—and not just from the clueless outsider, but from some mainstream economists as well. Yet, little has changed” (p. 1353).

Economics is forever in crisis, but never in flux. Thus, even the successful introduction of new analytical tools such as mathematical complexity theory and mathematical network theory has done relatively little to change the essential contours of mainstream economics. Macroeconomics and growth theory have proven particularly resistant to change. They continue to be dominated by models in which complexity and cambiodiversity are absent as are, therefore, *emerging* complexity and cambiodiversity.

Macroeconomics is dominated by "dynamic, stochastic, general equilibrium" (DSGE) models. As Koppl (2014 p.50) has explained, "DSGE models are dynamic because they describe the behavior of an imaginary economy over time. They are stochastic because some of the key variables of the model such as productivity and labor supply are subject to random shocks. Finally, they are general equilibrium models because all markets are considered at once".

By including "general equilibrium" in their name, DSGE models promise to represent an economy's vast network of microeconomic interactions. General equilibrium models represent the demand and supply of all traded goods and the set of prices that would bring all markets into equilibrium simultaneously. Walras (1871–1874) initiated this family of models. Debreu (1959) is a latter-day representative. Hotelling (1932) showed that general equilibrium can give rise to the sort of non-linearities that today we associate with complexity theory. He showed that "a tax on sellers of two commodities may result in both prices being lowered even under free competition" (1932, p. 385). More recent results also point to the potential complexity in general equilibrium models. Sonnenschein (1972, 1973), Mantel (1974), and Debreu (1974) showed that most properties of individual excess demand curves do not aggregate in general equilibrium, thus creating the possibility of multiple equilibria and unstable equilibria. Citing Hirsch et al. (1989) and Papadimitriou (1994), Axtell (2005) reports that computing the equilibrium price vector can be "hard" in the strict mathematical sense that "there are no polynomial time algorithms for the general case with nonlinear utility functions" (p. F196). (As Axtell explains, "Polynomial time algorithms… are those that can be realistically solved by computers" [pp. F196-F197].) Richter and Wong (1999) show that general equilibrium may not be (algorithmically) computable at all even if "all the agents' characteristics" such as "utility functions and endowment vectors" are computable.

The potential for complexity in general equilibrium models is not realized in DSGE models. As Koppl (2014, p. 50) notes, DSGE boils it all down to "a few equations representing, typically, one person, the representative individual, choosing how to distribute one good, labelled 'consumption', over time given a production technology that can change only when a random shock alters one or more coefficients of the equation linking a few inputs to the output of the one consumption good". The number of goods in such a "toy model" is generally less than 10, which contrasts with the roughly 10 billion goods available in New York City (Beinhocker 2007:9). DSGE models understate cambiodiversity by about 8 orders of magnitude. There are DSGE models with "endogenous product variety." Bilbiie et al. (2008 and 2019) are salient examples. Models with "endogenous product variety" were discussed above. Although they do have a form of cambiodiversity, they are nevertheless low-complexity models in which, typically, "product creation" is equated with "firm entry" (Bilbiie et al. 2008, p. 300).

By including "stochastic" in their name, DSGE models promise to represent uncertainty in the economy. Unfortunately, it is a very limited form of uncertainty. In a stochastic process, all possible states of the system are pre-stated. But, if there is a continual stream of novelty disrupting the system, the resulting uncertainty cannot be represented as the realization of a pre-existing probability density function (Knight 1921, Keynes 1921, Shackle 1972, O'Driscoll & Rizzo 1985).

Finally, by including "dynamic" in their name, DSGE models promise to represent a change in the economy. But such "change" consists solely of fluctuations in variables having time subscripts.

The situation in growth theory is not substantially better than in macroeconomics. Modern growth theory in economics is dominated by single-sector models. In such models, economic growth is represented as increases in a scalar value, as shown below:

$$Y_t = A_t K_t^{\beta} L_t^{(1-\beta)}$$

[Eq. 1]

In this equation, Y_t represents the overall output of the economy, which is typically equated with GDP. A_t is the “level of technology”. K_t and L_t represent the quantity of capital and labor, respectively. And, β is a weighting factor between zero and one. Output in any period is a simple function of the quantities of the total of all types of labor added up, somehow, by an unspecified process and the total of all types of capital added up by an equally unspecified process, all multiplied by a scalar value that is supposed to represent the “level” of technology. Solow (1956) is an earlier pioneering example of the sort of growth theory we are describing. Romer’s transformative 1990 article endogenized technological change. Jones (2019) provides a lucid and helpful discussion. This sort of highly aggregative model has many strengths. Solow showed powerfully, for example, that there is more to economic growth than capital accumulation and population growth. Like any model or model class, however, standard growth theory has its limits. In particular, it omits emergence, cambiodiversity, ramifying change, and biophysical constraints.

The Theory of the Adjacent Possible

Koppl et al. (2018) offer an alternative model of economic growth that exhibits increasing cambiodiversity. The core of their model is a remarkably simple combinatorial equation, which may be called the “TAP” equation. TAP is an acronym for Theory of the Adjacent Possible. It is thus an allusion to Stuart Kauffman’s idea of the adjacent possible (Kauffman 2000, pp. 142–144). The equation describes the evolution of cambiodiversity:

$$M_{t+1} = M_t + P \sum_{i=1}^{M_t} \alpha_i \binom{M_t}{i}$$

[Eq. 2]

where, M_t is the number of goods or tools in the economy at time t. The expression $\binom{M_t}{i}$ represents combinations of M_t things taken i at a time. In other words, it is $\frac{M_t!}{i!(M_t - i)!}$. The values α_i are between 0 and 1, and decline as i grows. The parameter P is a probability scaling factor such that $P\alpha_1$ is the probability that a new good will be formed by modifying one previously existing good, $P\alpha_2$ is the (smaller) probability that a new good will be formed by combining (perhaps with modifications) two previously existing goods, $P\alpha_3$ is the (yet smaller) probability that a new good will be formed by combining (perhaps with modifications) three previously existing goods, and so on. The declines in these probability values reflects the increasing difficulty of finding and testing useful combinations among an increasing number of goods. Steel et al. (2020) show analytically that a continuous-time version of the process reaches infinity in finite time. Thus, it has a singularity.

The TAP equation provides one explanation for the “hockey stick of economic growth,” whereby global income per capita was stuck below $4.00 per day before taking off about 1800 C.E. The TAP equation exhibits the same pattern of prolonged stasis followed by sudden takeoff, like that of biodiversity up to and including the Cambrian explosion. Figure 1, taken from Koppl et al. (2018), illustrates the hockey stick of economic growth and the behavior of the TAP equation. (Both figures were produced by Abigail Devereaux.) Koppl et al. (2018) provide a developed argument that the TAP equation may indeed be used to explain the hockey stick of economic growth. But they do not account for the emergence of new economic niches. Without a theory of niche emergence, their model of increasing cambiodiversity is incomplete. This paper helps to complete the picture by providing just such a theory.

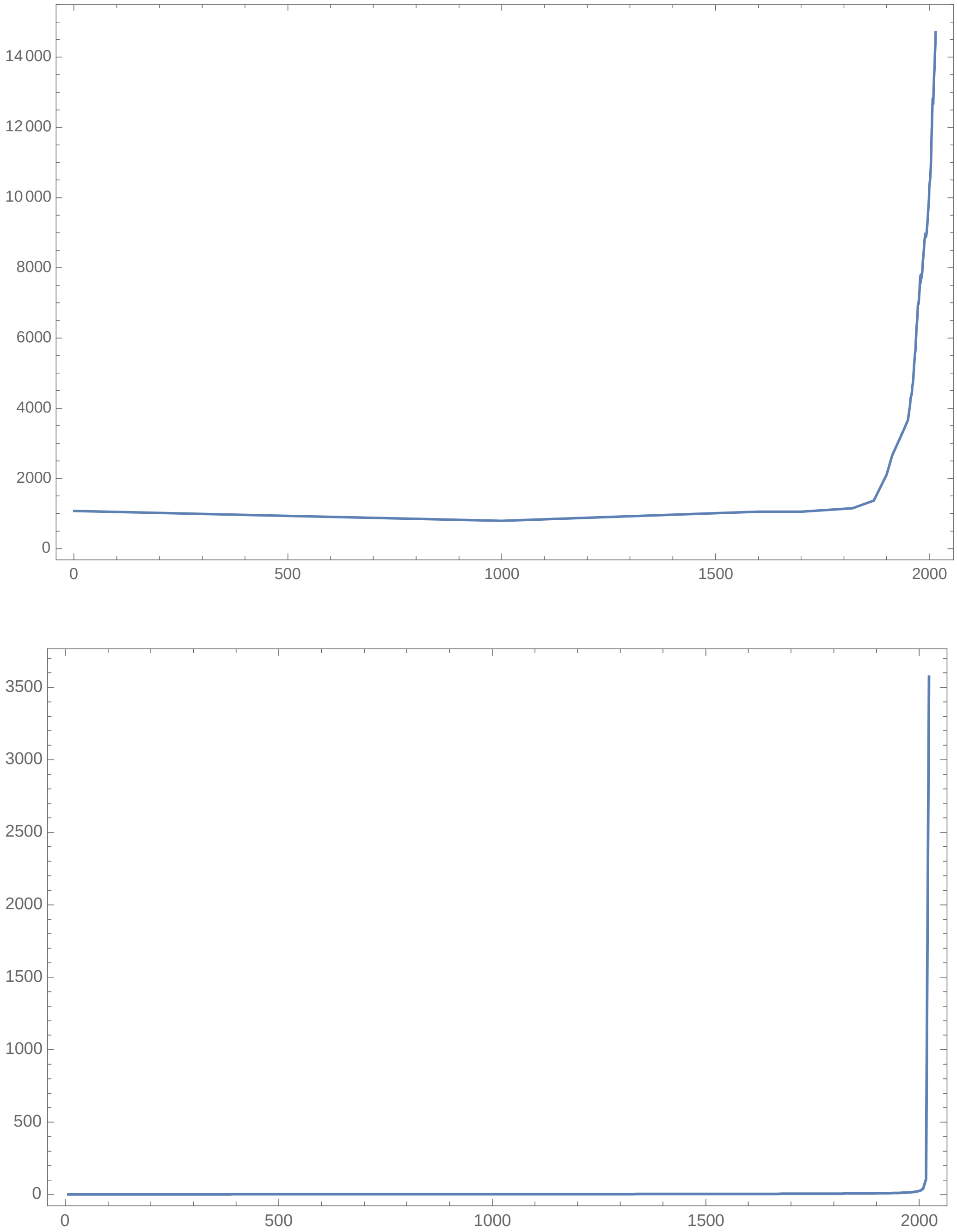

Figure 1 The top panel shows GDP per capita over the long run. The bottom panel shows the behavior of the TAP equation (*y*-axis), scaled from 0 to 2015 (*x*-axis).

Emergent economic niches mitigate competitive pressures

Ecological niches are filled by the best-fitted species or guilds of species. They are "best" compared to their rivals, but they will not generally be "optimal" from a design perspective. Natural selection grades on a curve. Although species can initially compete (or, better, find a way to avoid competition with others by ecological niche displacement (Ulanowicz 1997)), usually they evolve towards symbiotic relationships (symbiosis, mutualism, commensalism, etc.), shifting their interactions from competition to cooperation, which allows the emergence of even more potential ecological niches (Ulanowicz 1997, Fath 2007, Cazzolla Gatti et al. 2017, 2018). Similarly, economic niches are filled by best-fitted goods. And they are "best" only when compared to their rivals. They may not be optimal from some absolute point of view. Market competition grades on a curve. These "best" goods co-evolve in the "economic web" of all the goods related as competing and completing goods (Matutinović 2002, 2005). As noted above, new goods typically come into existence as competing to some currently existing goods and completing to others. Hence, the web evolves into its “adjacent possible” sucked into the very opportunity it itself creates (Kauffman 2019). More, although companies or workers can initially compete, they often find ways of avoiding competition with others by economic niche displacement, which may produce an outcome similar to monopolistic competition. A firm may occupy a unique economic niche because it has differentiated its product. Such differentiations may help a set of potentially rivalrous firms to evolve towards "symbiotic" relationships (cooperatives, holdings, etc.), shifting their interactions from competition to cooperation, which allows the emergence of even more potential economic niches.

Agent heterogeneity is endogenous in our model, which allows us to avoid the sort of paradoxes explored by the economist G. B. Richardson (1960, 2003). He has fun with paradoxes created by the economist’s notion of “perfect competition.” In a “perfectly competitive” market, you have an infinite number of potential entrants waiting to enter a market. The slightest sliver of “economic profit” induces entry. But, Richardson asks, if we assume (as the theory does) “perfect information” won’t all of those infinitely many potential entrants enter? But if they do, won’t the resulting massive entry induce massive losses? Anticipating this, won’t they abstain from entering? In this perfect competition scenario, the profit opportunity everyone knows about goes unexploited. And so on. Richardson (1960, p. 248) says, “[a] profit opportunity which is available equally for everyone is, in fact, available to no one at all.” The logic here is not so different from Brian Arthur’s (1994) El Farol problem. El Farol is a small, local bar, and common after-work hang-out place in Santa Fe, New Mexico. Given the size constraints of the bar if too many people went on the same evening (Thursday, in the original formulation), then the large crowd would diminish each individual’s experience. However, and in contrast, if too few people went to the bar that evening, then the experience was also sub-optimal for lack of critical participation. The point is there is no equilibrium solution that can be worked out in advance. The situation creates a kind of permanent disequilibrium in part because the best choice (go or don’t go) for each individual depends on the unknown choices of all the other individuals. The self-referential nature of the problem calls for approaches quite different from those of standard economics.

An important part of what drives Richardson’s paradoxes is the assumption of agent homogeneity. Without the notion of an economic niche, the notion of agent heterogeneity is ad hoc. By introducing the notion of niche, we are able to make agent heterogeneity endogenous. This resonates deeply with Adam Smith’s ideas on human equality, which he expressed forcefully in the second chapter of *The Wealth of Nations*. In fact, a cornerstone concept in ecology is the Competitive Exclusion Principle, which states that no two species can occupy the same niche, thus, invoked as a driver for species diversification and niche creation. The ensuing heterogeneity stabilizes competitor dynamics, avoiding their competition. Something similar seems true in economics: in economic niches, differences reduce inter-firm competition and enhance the number of coexisting firms.

In the economy, goods and services afford niches for not yet existing competing and completing goods. For example, word processing on personal computers afforded the possibility to share files and created a niche for a new good: the modem. But there was not a complete market for modems before their invention. Someone saw the new opportunity and seized that opportunity to make and sell modems. This gets to Richardson’s paradox. Without the notion of an economic niche, the modem is an opportunity for everyone and thus, perhaps, for no one. But, if we recognize the role of niche emergence and the paucity of parties proximate to a newly opened niche, then we can avoid Richardsonian paradox. Competitive General Equilibrium (CGE) cannot help us work out the dynamics of innovation because it requires us to prestate all dated contingent goods, which is to say that it assumes away novelty. We could not prestate the to-be-invented modem. Thus, again, we need to look in a new direction, namely, toward a theory of economic niche emergence.

Thus, we arrive at a sensible notion of "economic niche". In economics, the word "niche" is used often enough to represent a specialized market at the macro scale, or the activity an individual is best fitted for at the micro-scale. However, we do not know of any good clear analysis of what, precisely, an economic niche might be. Here, we attempt to formally define a notion of economic niche adumbrated in Koppl et al. (2015) and show that this notion of "niche" is strongly related to that of “ecological niche” and is a missing piece from the theory of economic growth and development. Noting that niche derives from the Latin, *nidus*, meaning nest, the ecological context takes prior usage. In fact, economic growth models ignore cambiodiversity (as defined above). If the economy is an evolutionary system, then cambiodiversity must be central to economic growth, but we cannot have a fully coherent model in which cambiodiversity grows unless a model contains a coherent notion of “niche” and niche “emergence”.

A parallel between the ecological and economic niche

There is a parallel between a niche as a market and a species as a good or service. The economic web grows into its adjacent possible opportunities, and thus creates its own growing diversity, which leads to the growing econosphere, and the autocatalytic emergence of cambiodiversity.
For an ecosystem to function and to persist over time, several critical roles must be filled and maintained (in the role of completing the task), including energy acquisition (plants/primary producers), energy concentrators/dissipators (animals/consumers) and nutrient releasers (decomposers). Early humans, as hunter-gatherers, differed little from this arrangement. The arrival of agriculture greatly enhanced energy acquisition leading to both population growth and also non-agricultural specializations. This can be considered as an early instance of niche emergence in human societies. One could envision a primitive human “ecosystem” having certain roles: agriculturist, potter/brickmaker, builder, metallurgist, doctor, etc. leading to more and more specializations: soldier, shaman, governor, etc. Therefore, an ecological niche is the role and the position a species has in its environment (its food and shelter needs, its survival and reproduction strategies, its function in the ecosystem, etc.). The concept of a niche as the set of ecological requirements, from the reproductive to the alimentary ones, developed by Elton (1927) and improved by Hutchinson (1957) with his definition of hyper-volume, is a powerful tool for understanding the role of each species in its environment. These multidimensional spaces or hypervolumes that include all of a species’ interactions with the biotic and environmental factors (traditionally labelled as abiotic, but perhaps better thought of as conbiotic on Earth (Fath and Muller 2018)), led to the consideration of niches as fundamental ecological elements able to regulate species composition and relations within an ecosystem. For example, it has been suggested that niche differences stabilize competitor dynamics by giving species higher per-capita population growth rates when rare than when common, and that coexistence occurs when these stabilizing effects of niche differences overcome species in overall competitive ability (Levine and HilleRisLambers, 2009). Moreover, it seems that nestedness of niches reduces interspecific competition and enhances the number of coexisting species (Bastolla et al., 2009).

Some authors suggested a relationship between the utilization of ecospace and change in diversity (Bambach, 1983). However, most of these previous studies emphasized the effect of niche partitioning as a global long-term pattern in the fossil record to explain the exponential diversification of life (Benton and Emerson, 2007). The main explanation for a pattern of exponential diversification is that as diversity increases, the world becomes increasingly divided into finer niche spaces. This explanation could be a result of the fact that nearly all studies of the impact of species interactions on diversification have concentrated on competition and predation, leaving out the importance of cooperative interactions (Joy, 2013). Moreover, this classical view is based on the idea that there is a pre-existing ecospace (ecological niche) that is thereafter divided and partitioned, which does not take into account the unprestatable emergence of ever new “features and functions” (Kauffman 2000, 2008, 2016, 2019), hence the new unprestatable dimensions and emergence of the new niches (Cazzolla Gatti et al. 2018). However, the idea that interactions between species are important catalysts of the evolutionary processes that generate the remarkable diversity of life is gaining interest among ecologists.

Indeed, facilitation and niche emergence (processes that allow the colonization and presence of new species taking advantage of the presence of other ones by expanding the ecosystem hypervolume) play a major role in species coexistence, strongly increasing the biodiversity of an area (Fig. 2). With the “Biodiversity-related Niches Differentiation Theory” (BNDT), Cazzolla Gatti (2011) proposed that species themselves are the architects of biodiversity, by proportionally (possibly even exponentially) increasing the number of potentially available niches in a given ecosystem. The economic parallel is that existing goods and services are themselves available economic niches for potentially new goods and services to enter the economy as competing to some existing goods and completing to others (Kauffman 1988, 2008). If, as noted above, each new good has more than one possible relationship as competing or completing, then it creates more than one new economic niche and diversity explodes (Kauffman 2016, 2019).

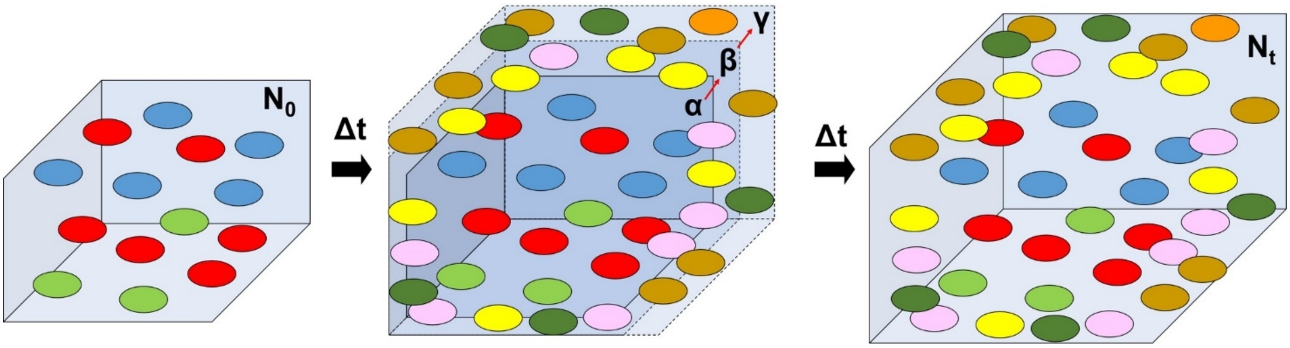

Figure 2 Niche emergence (α→β→γ) is a processes that allows the colonization and presence of new species taking advantage of the presence of other ones by expanding the ecosystem hypervolume (N_0) in an unprestatable way and, playing a major role in species coexistence during evolutionary time (Δt), strongly increases the biodiversity of an area (N_t)

We have also recently argued that biodiversity can be viewed as a system of autocatalytic sets (EcoRAF sets) and that this view offers a possible answer to the fundamental question of why so many species can coexist in the same ecosystem (Cazzolla Gatti et al. 2017). An *autocatalytic set*, as originally proposed by Kauffman (1986, 1993) and now defined in the context of chemistry, is a chemical reaction network in which all reactions are catalyzed by molecules from the set itself (“reflexively autocatalytic”, or RA), and all molecules can be made from a basic food source by using only reactions from the set itself (“food-generated”, or F). Thus, an autocatalytic set has catalytic closure (it creates its own catalysts) and is self-sustaining on a given food set (Hordijk & Steel, 2017). An example is shown in Figure 3.

An ecological niche is clearly not only defined by the environment (in this case the original food/resource set *F*), but also by other species and guilds that are already present in an ecosystem (EcoRAFs), and which generate an extended food (or resource) set. Thus, the existence of one or more species enables the evolution and establishment of other species in the same ecosystem. In short, new species create new niches (Fig. 4). In this way, we claim that biodiversity is autocatalytic and that increasingly diverse ecosystems are an emergent property of evolution (EvoRAFs). Thus, diversity of species expands in a species-rich environment, which is created by the diverse use and reuse of received energy.

In the ecological theory "niche emergence" is a neglected process, while "niche partitioning" has been widely used as a hypothesis to explain species coexistence and evolution. The emphasis put on niche (resources and conditions) partitioning for new niche evolution has hidden the reality: there is a limited possibility to prestate niches in the ecosystems because niches emerge when new species colonize the space or evolve in time (Cazzolla Gatti et al. 2018).

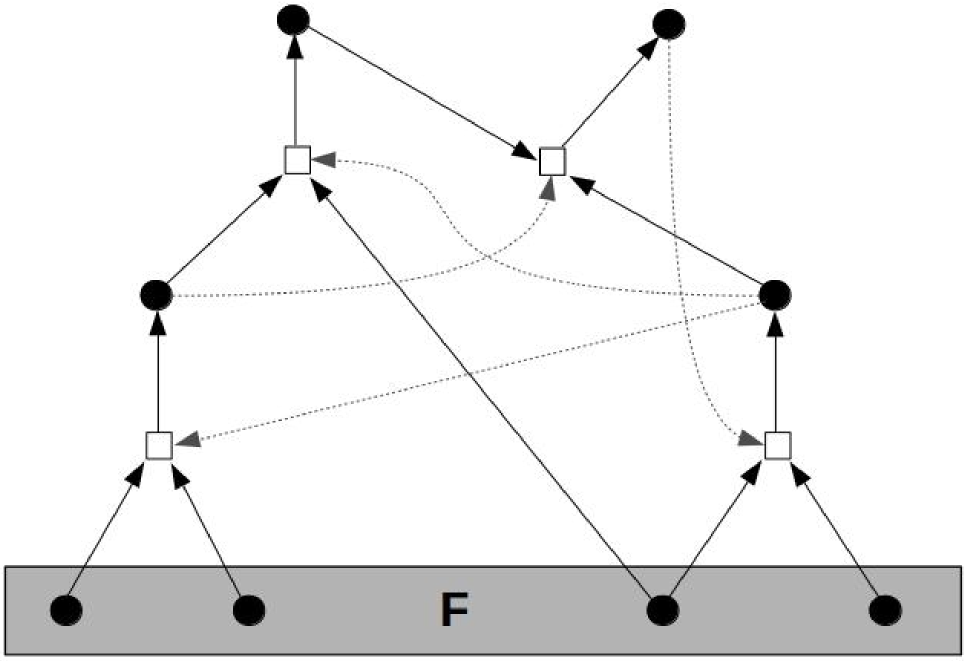

Figure 3 A simple example of an autocatalytic (RAF) set. Black dots represent molecule types, white boxes represent reactions. Solid arrows are reactants going into and products coming out of a reaction. Dashed arrows indicate which molecules catalyze which reactions. The food set F consists of the four molecule types in the gray box

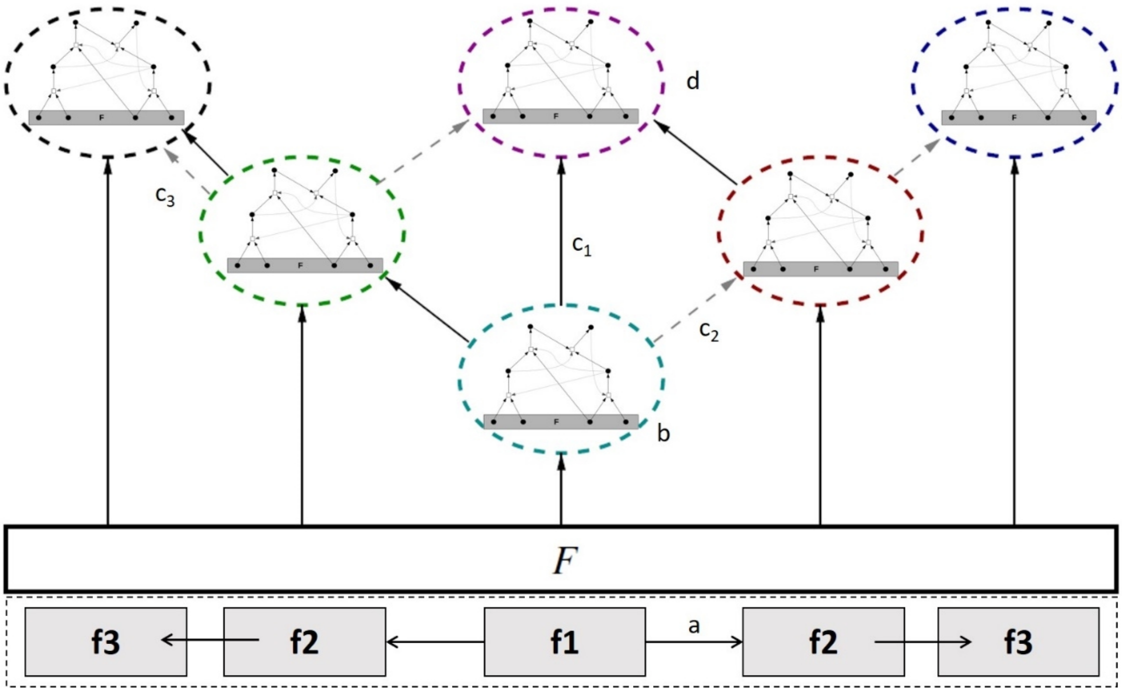

Figure 4 An example of how existing species can enable new species in an ecosystem (EcoRAF sets). Species (b), which can exist entirely on a given conditions and resources set (f1), might create some conditions and resources (f2, f3) that is required by other (potential) species catalyzing, either directly (solid arrow, c1), indirectly (dashed arrow, c2) or both (c3), thus “expanding” the conditions and resources set and enabling other species (d) to come into existence by evolutionary autocatalysis, thus creating an EvoRAFs

This provides a formal view on an evolutionary time scale. So, we have different levels of aggregation (hierarchical autocatalytic sets), which correspond to different time scales. Each set enables the (partly) unprestatable emergence of a new one. Each species, by realizing its ecological niche during the evolutionary timescale, facilitates the emergence (or the expansion) of new niches (Cazzolla Gatti et al. 2017, 2018). As Jane Jacobs (2000) observed, “the ensemble itself made the environment rich by expanding” (p. 45) as the first stage of emergence, followed by specialization and partitioning during which, “an ensemble grows rich on an environment that the ensemble itself made rich” (p. 60).

An example may help clarify this theory of niche emergence. Pilotfish (*Naucrates doctor*) clean shark teeth. The shark opens its mouth and lets the pilot fish in. It seems hard to conceive of this tooth-cleaning niche as existing, somehow, before the emergence of a relatively large swimming animal with teeth. Thus, it seems inappropriate to think of this tooth-cleaning niche as the product of a subdivision of some larger, pre-existing niche. Rather, the niche emerged together with shark teeth. The shark’s evolutionary arrival brought with it multiple niches that cannot plausibly be thought of as existing previously. The niches created by the shark’s existence are not a function of the shark alone. The existence of other species in the ecosystem creates, as it were, interaction opportunities that further multiply the number of niches created by the evolutionary arrival of sharks. The Biodiversity-related Niches Differentiation Theory (BNDT) of Cazzolla Gatti (2011) shows that the number of ecological niches in the system expands with the number of species either exponentially or as a power law. Thus, as the system evolves the number and variety of niches ramifies and biodiversity grows. Our point is that cambiodiversity in the econosphere grows by a parallel process.

Autocatalytic and emergent economic niches

Here, we argue that the economy can also be viewed as an autocatalytic (RAF) set, just like ecosystems, which can explain the phenomenon of niche emergence also in economic systems (Kauffman 2016, Hordijk and Steel, 2017). First, consider economic production functions as the equivalent of chemical reactions, transforming a certain number of “input” goods into a certain number of “output goods”. For example, several pieces of wood and metal can be used to produce a wheelbarrow. Next, consider the “facilitation” of such production functions as the equivalent of catalysis in chemistry. For example, a hammer can act as a “catalyst” for making wheelbarrows: it is not used up in the process, but it increases the rate at which wheelbarrows can be made. Finally, observe that the hammer itself is the product of some other production function in the same economy and that its use is not necessarily limited to making wheelbarrows. Its multi-functionality gives it many ways to contribute to new product development, thus extending its own usefulness (fitness).

In this way, an economic network forms a self-sustaining autocatalytic set: all production functions are “catalyzed” (facilitated) by-products of the same economic network, and all these products can be made from a basic set of raw materials, analogous to the food sets we discussed above, by using production functions from this same economic network. A simple example of an “economic RAF set”, which shows emergence of economic niches, is presented in Figure 5.

In conclusion, with this novel interpretation of the economic niche and its emergence based on an ecological analysis of the autocatalytic properties of niches, we argue that diversity itself – both in ecology and economy - creates yet more diversity. In this sense, we may say that biodiversity and cambiodiversity are “autopoietic.” The system is “sucked into” new opportunities. Moreover, we stated that ecosystems in ecology and market systems in the economy are both autocatalytic sets.

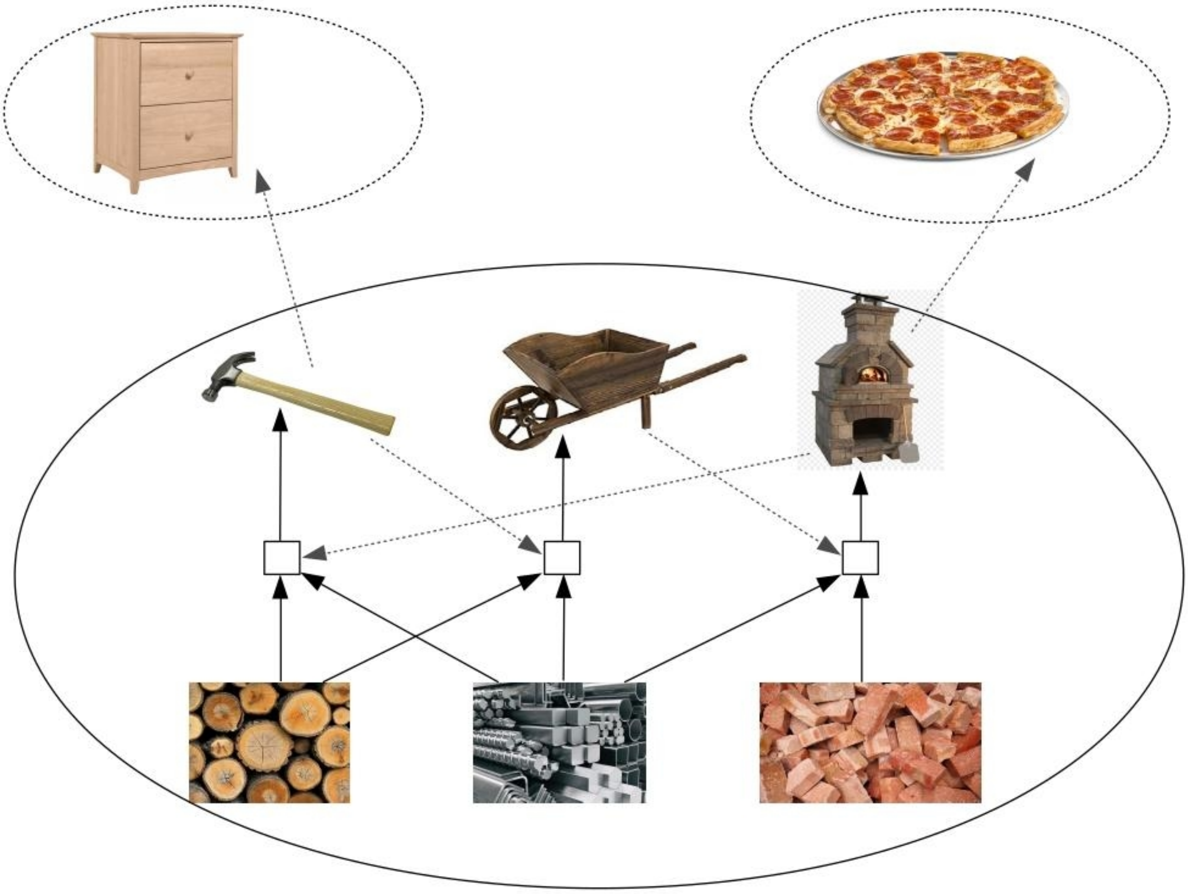

Figure 5 The main idea behind an "economic RAF set". The food set consists of wood, metal, and bricks. These can be combined in different ways to produce hammers, wheelbarrows, and brick ovens. Each of these products can also act as a catalyst: a hammer speeds up the production of wheelbarrows (without being used up in the process), the wheelbarrow speeds up the transportation of bricks to make ovens, and the oven speeds up the production of hammers by melting the metal so it can be molded into the right shape. This "economy" as a whole (within the solid oval) thus forms an autocatalytic set. Once this set is established, it may allow the emergence new "economic niches" that were not possible before (the dashed ovals)

In the light of this, we find classic models of economic growth, while (of course) illuminating and important, omit an important feature of economic growth that seems to merit closer consideration. They omit cambiodiversity and its increase over time. More traditional economic models ignore economic system autocatalysis and niche emergence. This omission is similar to the omission in most ecological models whereby, for instance, they try to predict optimum fishing strategies without taking into account that species catalyze each other's existence in autocatalytic ecosystems (Cazzolla Gatti et al. 2017) and, in this way, allow the emergence of new ecological niches available for other species (Cazzolla Gatti et al. 2018).

As we have seen, the theory of niche emergence suggests a possibly nonstandard view of the relationship between competition and cooperation. The ramification of niches allows potential competitors to occupy distinct niches between which competition is weaker or nonexistent. Ulanowicz's (2009) analysis of the "centripetality" of autocatalytic processes develops the point. The elements in an autocatalytic set move in emergent paths of self-reinforcing interdependence. But this mutualistic self-reproducing nature of the process can be disrupted by the arrival of a competitive element that draws energy or resources toward itself and away from the incumbents it is competing with. "That is, selection pressure and centripetality can guide the replacement of elements" (p.1889). We may draw the inference that, following Ulanowicz, "competition is *subsidiary* to centripetality," which, in turn, "rests on *mutuality*" (1888). If we are right to view "market competition" as autocatalytic, then the competitive element, though important and real, rests on mutuality. In other words, the "competitive market process" is first and foremost a cooperative social process.

Broadly similar views of the relationship between competition and cooperation have been expressed in the past. Smith (1776) said that "it is by treaty, by barter, and by purchase, that we obtain from one another the greater part of those mutual good offices which we stand in need of." Hayek said, "The function of competition is here precisely to teach us *who* will serve us well: which grocer or travel agency, which department store or hotel, which doctor or solicitor, we can expect to provide the most satisfactory solution for whatever particular personal problem we may have to face" (1948, p. 97, emphasis in original). More recently, Rubin (2019) comes much closer to our point when he says, "competition is subordinate to cooperation in an economy," even though, "there is an important role for competition." Kropotkin (1902) might at first seem to be another anticipator, at least in broad strokes. But he saw "competition" and "mutual aid" as alternatives and thought only that we rely too much on the one and too little on the other. It is our view, instead, that market competition rests, ultimately, on a logically and temporally prior mutualism among human actors.

The relationship between competition and cooperation is in part a matter of "mere semantics." But our theory of niche emergence together with Ulanowicz's analysis of mutualism and centripetality puts analytical flesh on the semantic bones of the issue. The technosphere is an autocatalytic system whose evolution produces a ramification of niches over time. The ramification of niches often allows potential competitors to move into distinct niches, thus avoiding or mitigating direct conflict of interest. Because the technosphere is an autocatalytic system, it consists of mutually supporting and reinforcing cooperative elements. Competition helps to reshape the system and to determine which parts fulfill which functions. Such competition is vital and necessary in part because of the non-mechanistic aspects of the system Ulanowicz points to. With autocatalytic systems, he explains, it is, "impossible to state apriori all the possible *complex* events that could perturb an element or a relationship, much less to specify the direction in which it might move the system" (2009, p. 1889, emphasis in original). Koppl et al. (2015) say that entrepreneurs (not central planners) do the reframing Ulanowicz points to. Thus, competition is real, necessary, and salutary, but also subordinate to mutualism and cooperation. It is an aspect of mutualism and cooperation.

Homo tinkerus

Our theory suggests a relatively modest role for human reason and foresight in the evolution of the technosphere and, therefore, in economic growth. The image in figure 6, which was discovered by Brain Arthur, may help to suggest how little vision, foresight, and inspiration are involved in any one technological innovation. The figure shows the DeWitt-Clinton locomotive in action along the Mohawk & Hudson line in 1831. (See unattributed 1920, 1921). The Mohawk & Hudson railroad combined rails and a locomotive, familiar from coal mining, with carriages familiar from horse-drawn passenger transport, thereby creating an early passenger railroad, which ran between Albany and Schenectady. It cobbled together existing elements with some tweaks along the way, such as modifying the wheels on the carriages. Similarly, early automobiles were truly horseless carriages. The early pioneers of digital computing did not imagine word processing, Facebook, or flash mobs when designing silicon chips. And their designs were, at every stage, relatively modest tweaks and combinations of previously existing elements. Again, technological innovation is cobbling together existing elements with a few tweaks along the way.

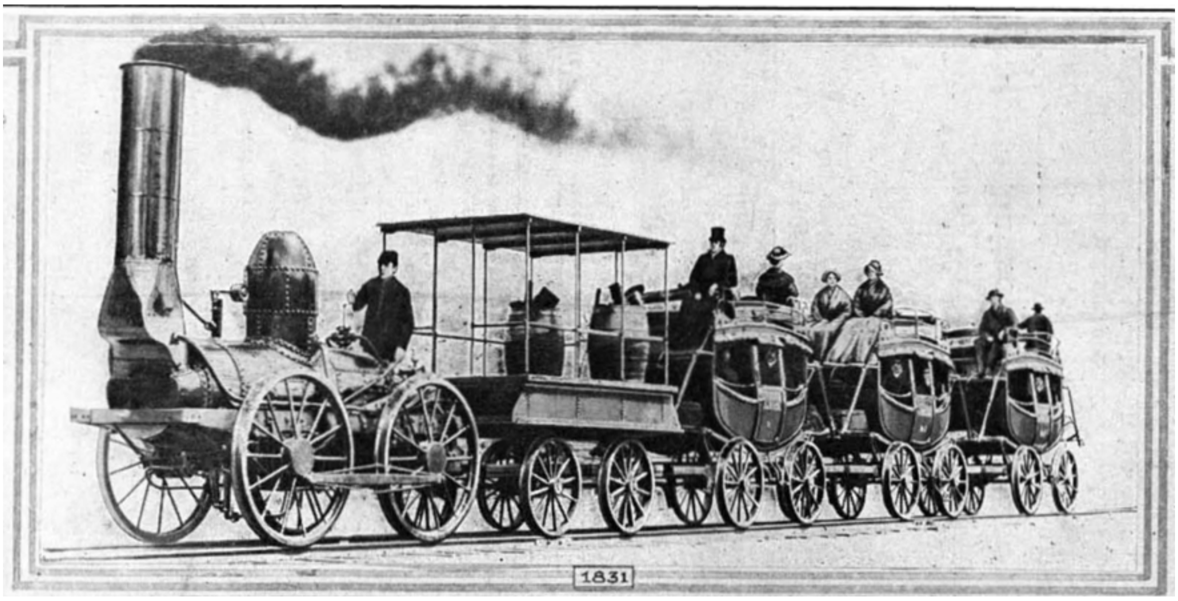

Figure 6 The image shows the DeWitt Clinton locomotive pulling coaches on the Mohawk & Hudson Railroad. The image was published in the Scientific American in 1920 (Unattributed 1920).

It is generally only after the economic niche has been opened by an innovative product that feeble human minds can imagine the niche and find some combination of existing elements, possibly tweaked a bit, to fill it with. Even the most creative entrepreneurs do not so much create opportunities as discover already opened niches and ways to fill them. In this sense, we may say with Kirzner (1973, 1982, 1997) that they "discover" pre-existing and "objective" opportunities. And even then, only a fraction of open niches, only a fraction of the "objective" entrepreneurial opportunities out there, are likely to be filled in any period. Someone must notice the open niche, and humans are not alert enough to see more than a relatively small portion of them.

Technology evolves when tinkering humans cobble together existing elements. In retrospect, at least, the early versions of a new technology often seem inelegant, clunky, unimaginative. Inelegant technological tinkering has probably been going on since our pre-human ancestors began making stone tools some 3.3 million years ago (Harmand et al. 2015). (If Harmand et al. are right, knapped stone tools emerged *before* the genus *homo*.) Tinkering with tools may be something like 3.3 million years old. (It is controversial, however, whether, for example, Acheulean technology might have been genetically rather than culturally transmitted or even required intergenerational transmission at all. See Shipton and Neilson 2018.) The TAP process of equation (2) probably began at about the time composite tools emerged, some 300,000 years ago (Ambrose 2001), or perhaps 400,000 years ago (Thieme 1997), or perhaps 500,000 years ago (Wilkins et al. 2012), although parameters such as P may have stabilized only much later. If anatomically modern humans emerged 200,000-300,000 years ago (Stringer & Galway-Witham 2017), then the TAP process may have begun at or *before* the arrival of anatomically modern humans. If "thinking" is something close to standard economic "rationality" and if the evolution of the technosphere is governed by a process that emerged prior to modern humans, then "thinking" may play a smaller role than tinkering in the evolution of the technosphere. Technological progress comes not from some Socratic thinkery, but from a Darwinian tinkery.

If progress comes from tinkering, not thinkering, then we may justly speak of "*Homo tinkerus*." Jacob (1977) suggests the metaphor of evolution as tinkerer. Kauffman (2019) has used the term "jury-rigging." Levi-Strauss (1967) used the roughly equivalent term "bricolage," which has gained currency in management and entrepreneurship (Weick 1993, Garud and Karnoe 2003, Baker and Nelson 2005) and in law (Hull 1991 p.317, Meyer 2014, Timmer 2015 p. 275). The words "tinkering" and "bricolage" are often used interchangeably. But some aspects of Levi-Strauss's original characterization of “bricolage” may be inappropriate for our theory of technological change. The “bricoleur,” Levi-Strauss tells us, “is adept at performing a large number of diverse tasks,” their “universe of instruments is closed” and “bears no relation to the current project.” Their tools are only things that “may always come in handy” (pp. 17-18). Thus, the word “bricolage” may have some tendency to inappropriately suggest a lack of specialization and even an aversion to novelty, whereas the most “rational,” planful, and advanced specialists in any technological domain are tinkerers.

When considering technological change, we should model humans as tinkerers, cobbling together existing elements as well as they can, adjusting, tweaking and combining in an unending process of trial and error. Technological change is not so much the product of reason, intelligence, and foresight as of tinkering and improvisation. To be sure, only a creature that is highly intelligent by biological standards could perform the required tinkering. *Homo tinkerus* must *understand* the domain in which they tinker. (We thank Brian Arthur for impressing this point upon us in correspondence.) Thus, for us, tinkering is a form of intelligent search. As such, tinkering is not often *completely* random, *ad hoc*, or arbitrary notwithstanding the random, *ad hoc*, and arbitrary elements in it. Instead, tinkering is generally aimed at filling a recently opened niche. The Wright brothers were *trying* to achieve heavier than air powered flight. But they did not so much design their way there as tinker their way there. And, they could not have gotten on the right path until the relevant technological niche had opened up, which is to say that both gliders and internal combustion engines had to exist before the Wright brothers and others could begin experimenting with ways to cobble them together.

This tinkery vision of technological progress may seem less surprising if we recognize the importance of tinkering in research science. Knorr (1979, p. 350) insists that “the mechanisms ruling the progress of research are more adequately described as successful ‘tinkering’ rather than as hypothesis testing or cumulative verification.” Biologist Kenneth Noriss (1991, p. 107) says, “Science is tinkery business.” Kantorovich (1993, p.3) argued that tinkering “is part and parcel of the very nature of scientific discovery and human creativity in general.”

Discussion

We believe our theory matters. It has, we believe, potentially important implications for economic science. We recognize that economic science serves multiple purposes while having itself no particular purpose. Like the human society in which it is embedded, economic science is a community with heterogeneous groups and individuals pursuing diverse and sometimes contradictory ends. We cannot stipulate for others what theory they should endorse. We can only submit our case humbly before our peers. And it would be hubris and error to stipulate what methods of inquiry others should use. We endorse the wisdom of physicist Percy Bridgman (1955, p. 535), who said, “The scientific method, as far as it is a method, is nothing more than doing one’s damnedest with one’s mind, no holds barred.” And yet we think our ideas matter and may deserve a place in the firmament of economic theories and methods.

Before considering some of the more challenging implications of our approach to economic growth, we might note a few relatively conservative implications. First, there is a connection between our “TAP equation” (equation 2 above) and standard economic growth models as represented above by equation (1). We may model the “level of technology,” A_t, with our measure of “cambiodiversity,” M_t. It seems relatively straightforward, then, to fold the TAP equation into a standard growth model. Doing so ensures that the resulting model will generate the hockey stick of economic growth (see Koppl et al. 2018.) Second, as we have noted above, our theory links complexity to wealth via cambiodiversity. This gives us something in common with complexity economists such as Beinhocker (2007), Hidalgo et al. (2007), and Arthur (2009). And, indeed, our approach uses complexity tools to study economic growth. Our project seems to have some less conservative implications, as well, to which we now turn.

Our theory links economics and biology in what may be a somewhat innovative fashion. Many figures have recognized some sort of connection between economics and biology. Darwin attributed his breakthrough insight (that "favorable variations would tend to be preserved and unfavorable ones to be destroyed") to Malthus (Darwin 1958, pp. 42-43). And many economists, of course, have borrowed in one way or another from biology (Veblen 1893, Alchian 1950, Hayek 1988). Barkow, Cosmides, Tooby (1992), Hodgson and Knudsen (2010), Burnham (2013), Burnham, Dunlap & Stephens (2015), and Lenski and Burnham (2018) provide examples of scholars going beyond mere borrowing to produce an integrated approach to biology and social science. Our theory of technological change offers an additional path to such an integration of the social and biological sciences. As we have noted, the TAP process of technological change may have arrived at about the time of anatomically modern humans or, perhaps, well before. It seems possible, then, that the tinkering behavior underlying the TAP process or, through multi-level selection (Sober and Wilson 1998, Wilson and Wilson 2007), the TAP process itself may be a biological adaptation. If so, then it would seem to unite modern social science, anthropology, archaeology, and the evolutionary history of *Homo*. Apparently, the TAP process cannot be understood as the product of some sort of modern and civilized "rationality." It is, instead, a "natural" process that emerged from the evolution of the hominin line.

If the process of technological change is "natural" in the sense we have suggested, it may not be possible for humans to self-consciously manage it. Reason, intelligence, and foresight have played relatively modest roles in the evolution of the technosphere. Technological change is "autopoietic (or self-creating)," as Arthur (2009 p. 170) notes. We do not see how to avoid a potentially disturbing conclusion: Technological change is not something *we do*; rather, it happens *to us*.

We do not wish to deny that human (and, early on, pre-human) actions were present at every moment in the technosphere's evolution. Tinkering is acting. But in none of those moments was the actor inventing the technosphere or controlling the whole of it. In the main, we are technology takers, not technology makers. The situation is much the same with language, which is, after all, a kind of technology. Even giants such as William Shakespeare were mostly language takers. Each utterance is a human act that occurs within a language but does not create a language. This is so even though those same utterances propel the evolution of the language over time. None of us decided that visiting first one website and then another should be called "surfing" rather than "navigating." And yet it was our many communicative decisions that brought about that result. It is much the same with technology. Every innovation occurs within a larger and pre-given technosphere. This is so even though those same innovations propel the evolution of technology over time.

Several conclusions seem to follow from the view that technological change happens *to* us.
The view that technological change happens to us seems to suggest an important sense in which social institutions such as legal systems are relatively unimportant in economic growth. If we take a sufficiently short-run perspective, of course, they matter greatly. The difference in outcomes between the two Koreas rather evidently depends on their two very different institutional structures. Pak (2004, p. 514) found that young adults in South Korea were more than two inches taller than their peers in North Korea (see also Schwekendiek 2009). On longer runs, social institutions seem neither neatly exogenous nor neatly endogenous. If we take the extremely long-run perspective of hundreds of millennia, however, social institutions such as legal systems are emphemera. Empires rise and fall, but the TAP process of technological change persists.

Our treatment of institutions may reflect the influence of biology on our thinking. In his classic article, "Time in Biology," J. B. S. Haldane (1956, p.398) said, "It is clear that the different time scales used in biology require different types of thought. Further, our knowledge about the events on these scales is based on different sets of facts." He illustrated this principle by providing very distinct answers to the question "Why does the male chaffinch sing in spring as he does?" (Haldane 1956, p. 388). He gives five very different answers, each appropriate for a different timescale. In the shortest timescale, the answer is that certain "muscles contract as the result of transformations of adenosine triphosphate and other substances." At one of the intermediate timescales the answer is that "longer spring days" have "produced hormones which act on his brain." And on the evolutionary time scale, it is because it yields and evolutionary advantage "that small birds should sing . . . to repel other males."

In the spirit of Haldane, we ask why this mouse pad being offered for sale. On a relatively short timescale, it is because the store manager ordered it from a wholesaler. On a longer timescale, it is because there is a recognized demand for mouse pads. On a still longer timescale, it is because *Homo tinkerus* has long sought to reduce calculation costs, which has led to a long series of innovations from positional notation, to the slide rule, to modern digital computing. Whether the recognized demand for mouse pads induces a ready supply depends on institutions. In this and related senses, we strongly concur with the consensus view of economists that "institutions matter" (Durlauf 2020). But when we stretch the timescale beyond what is customary in economic inquiry, institutions are transformed from cause into effect. For at least some actors, any technological innovation will raise the opportunity cost of institutions that prevent or discourage the use of it. This increase in opportunity cost tends to create pressure for institutional change. Each innovation is but one grain of sand, which will usually have little power to change institutions. But, the accumulation of many such grains will eventually unleash an avalanche of institutional change. Most such avalanches will be small, but a few will be big, and a very few will be very big (Bak et al. 1987). Because the different time scales used in economics require different types of thought, we cannot expect an unequivocal answer to the question whether institutions matter. Strictly speaking, the question is incoherent. At what timescale? There are different time scales in economic inquiry, and our knowledge about institutions on these scales is based on different sets of facts.

In the extremely long run of scores of millennia or longer, institutions are endogenous. But because of path dependency, an ephemeral social institution may have enduring consequences. The institutional ecology of a moment will make some technological innovations more likely and others less likely (Cazzolla Gatti 2016). It thus influences the technosphere's path through the vast and unprestatable space of possibilities in much the way Arthur (1989) described lock-in by historical events.

The TAP process of technological change tends to give power to those enriched by it. For most of human history, only a small portion of the population was enriched by the process of technological change. Thus, too much of history has been a dismal tale of back and forth change in who was oppressing whom. After about 1800, the TAP process began to enrich the masses. In England and Wales wages rose right from the start of the Industrial Revolution (Engerman 1994, Clark 2001, 2005, Griffin 2018, p. 74). This "Great Enrichment" (McCloskey 2016) allowed "liberal" institutions such as democracy to spread.

Once the TAP process began to enrich more than a small elite, power grew more diffuse in society. Consider the history of the elective franchise in the United Kingdom. The first great reform came in 1839, relatively soon after the Industrial Revolution had lifted GDP per capita substantially. A series of reforms followed thereafter, which expanded the vote to more and more persons including, ultimately, both men and women with no property restrictions. First, technological progress. Then wealth. Then democracy. This crude pattern is a good approximation for the global spread of democracy, which came mostly after the Industrial Revolution, not before. (See, e.g., Boix et al.2013, especially Figure 2 on page 1538.) Acemoglu et al.'s (2019) result for the period 1960–2000 that "democracy does cause growth" points to feedbacks and the need for subtlety. With due recognition of interaction effects, such results do not seem to contradict our first-order approximation that wealth has been the great historical driver of global democratization. Roughly, the people were first enriched and then, subsequently, wrested their rights and liberties from the powerful. Of course, this story of emancipation has its ups and downs as well, and the enormity of some of the "downs" may be hard to exaggerate. And yet, the global trend since the Industrial Revolution has been decidedly emancipatory.

The spread of wealth and democracy has been accompanied by improvements in more or less all metrics of life quality. About twenty years ago, Richard Easterlin (2000, p.7) could say, “Most people today are better fed, clothed, and housed than their predecessors two centuries ago. They are healthier, live longer, and are better educated. Women’s lives are less centered on reproduction and political democracy has gained a foothold.” People today live longer, healthier, freer, more meaningful, less painful, and more literate and cultivated lives than in the past. While these improvements have not, of course, spread uniformly or universally, “it is the greatest advance in the condition of the world’s population ever achieved in such a brief span of time.” The process has not run its course. Today there remain probably about 680 million humans living at or below the “absolute poverty” level of about $2.00 per day (Roser & Ortiz-Ospina 2017) and billions remain in relative poverty. But the numbers have been improving. In 1820, probably about 94% of the globe’s population lived in absolute poverty. Today, it seems to be less than 10%. And the absolute number in absolute poverty has been falling. “The number of people in extreme poverty has fallen from nearly 1.9 billion in 1990 to about 650 million in 2018” (Roser & Ortiz-Ospina 2017).

If we are right to somewhat downgrade the role of institutions, then, for better or worse, we must also downgrade the role of ideas. And Haldane’s logic from “Time and Biology” seems to apply to the role of ideas in society in much the way it applies to the role institutions. Whether ideas are cause or consequence depends the timescale. And, like the institutional ecology of a moment, the ideational ecology of a moment will make some technological innovations more likely and others less likely. Thus, it, too, influences the technosphere’s path through the vast and unprestatable space of possibilities in much the way Arthur (1989) described lock-in by historical events.

If we downgrade ideas, then we may have to reconsider the role of experts in driving economic growth. John Maynard Keynes thought that “the ideas of economists and political philosophers” were so important that “the world is ruled by little else” (1936 p. 383). Our theory seems to suggest a more peripheral role for ideas. Karl Marx, of course, had an extreme version of the view that culture is the product of its material foundations. (See Marx 1904, pp. 12–13 for a pithy summary.) We recognize with Bhaskar (1991) and others that Marx can be hard to interpret. But it seems fair to say that Marx’s “historical materialism” lacks clear and plausible mechanisms among other difficulties. Nevertheless, the general view that a person’s ideas reflect their material foundations is hardly unique to Marx. Upton Sinclair (1994, p.109) famously quipped, “It is difficult to get a man to understand something when his salary depends upon his not understanding it!” In other words, our ideas may be at least to some degree the product of a rough and ready calculus of costs and benefits. Julius Ceasar made a similar point when he said, “men generally believe quite freely that which they want to be true” (as translated by and quoted in Risinger et al. 2002, p. 6).

Ideas can matter greatly in relatively short runs. The abolitionist movement in the US, for example, was very much a product of moral ideas about liberty and brotherhood. But on longer views, we have said, empires and institutions come and go while the TAP process persists. But in that case, the ideas animating social institutions come and go as well. It seems only plausible, then, to suggest that ideas are endogenous in much the way institutions are. Just as democracy seems to be more an effect of wealth than a cause of it, the predominate social and political ideas of an age may be, at least in some cases, more an effect of wealth than a cause of it. Baumard et al. (2014) have argued that the “spiritual and moralizing religions” such as Buddhism that emerged “between the fifth century BCE and the third century BCE” (p. 10) may have been the product of “an increase in standard of living in the most affluent societies of antiquity” (p. 12).

Koppl (2018) takes a skeptical view of expert power while recognizing, of course, the value of expertise. Our theory seems to bolster such skepticism about expert power. Economists may need to reconsider their role as empowered "experts" attempting to engineer the system from on high. Standard economics takes an engineering approach in which the system is modeled as a relatively simple machine. But should economists really pretend to tell us, in effect, how to adjust the dials on the machine? If the "machine" is a ramifying ecology of the sort we have described, this engineering approach seems likely to go wrong. The Federal Reserve System, for example, was created in 1913 to prevent depressions. And yet the American central bank was unable to prevent the Great Depression of the 1930s or mitigate its harms. Nor did it prevent the "Great Recession" of 2007–2009. Selgin et al. (2012) review evidence showing that economic performance was worse under the Federal Reserve System than the prior National Banking system and that performance was little or no better even when we exclude the inter-war period. From our theoretical perspective, such failures of mechanistic expert-driven policy may seem almost inevitable. And, such repeated failure may help to explain why economics has been in constant crisis and will likely remain in constant crisis until a more organic and evolutionary model is widely adopted. We put our theory forward in the hope that it might in some way help others to develop less mechanistic and more organic models of economic development.

References

Acemoglu, D., Naidu S., Restrepo P., Robinson J. A. 2019. Democracy does cause growth. *Journal of Political Economy*, 127(1): 47-100

Agassi, J.1994. Review of Aharon Kantorovich, *Scientific Discovery: Logic and Tinkering*, Iyyun, *The Jerusalem Philosophical Quarterly*, 43: 339-347

Albert, Réka, Hawoong Jeong, and Albert-László Barabási. 2000. "Error and attack tolerances of complex networks," *Nature* 406: 378-382.

Alchian, A. A. 1950. Uncertainty, Evolution and Economic Theory. *Journal of Political Economy*, 58: 211-221

Ambrose, S. H. 2001. Paleolithic Technology and Human Evolution. *Science*, 291: 1748-1753.

Arthur, W. B. 2009. The Nature of Technology, Free Press, Simon and Schuster, N.Y.

Arthur, W.B. 1994. Inductive Reasoning and Bounded Rationality. *American Economic Review: Papers and Proceedings*, 84: 406–411

Arthur, W.B., "Competing Technologies, Increasing Returns, and Lock-In by Historical Events,"

Economic Journal, 99, 116-31, 1989.

Axtell, R. 2005. The Complexity of Exchange. *The Economic Journal*, 115: F193-F210

Bak, P., Tang, C., Wiesenfeld, K. 1987. Self-organized criticality: an explanation of 1/*f* noise. *Physical Review Lett*ers, 59 (4):381–384.

Baker, T., R. Nelson. 2005. Creating something from nothing: Resource construction through entrepreneurial bricolage. *Admin. Sci. Quart*, 50(3) 329–366

Barkow, J., Cosmides, L., John, T. (eds.) 1992. *The Adapted Mind: Evolutionary Psychology and the Generation of Culture*, New York and Oxford: Oxford University Press.

Beinhocker, E.D. 2007. *The Origin of Wealth: Evolution, Complexity, and the Radical Remaking of Economics*, Harvard Business Review Press, Cambridge, MA

Bhaskar, R. 1991. Knowledge, Theory of. In Tom Bottomore, Lawrence Harris, V. G. Kiernan, and Ralph Miliband, eds., A Dictionary of Marxist Thought, 2nd ed. Oxford and Malden, MA: Blackwell, pp. 285–94

Bilbiie, Florin O., Fabio Ghironi, and Marc J. Melitz. 2008. "Monetary Policy and Business Cycles with Endogenous Entry and Product Variety," *NBER Macroeconomics Annual*, (2007), 22: 299-353

Bilbiie, Florin O., Fabio Ghironi, and Marc J. Melitz. 2019. "Monopoly Power and Endogenous Product Variety: Distortions and Remedies," *American Economic Journal: Macroeconomics*, 11(4): 140-174

Boix, C., Miller, M., & Rosato, S. 2013. A Complete Data Set of Political Regimes, 1800-2007. *Comparative Political Studies*, 46(12): 1523-1554

Bridgman, P. W. 1955. *Reflections of a Physicist*. New York: Philosophical Library

Burnham, T. C. 2013. Toward a neo-Darwinian synthesis of neoclassical and behavioral economics. *Journal of Economic Behavior and Organization*, 90S: S113-S127.

Burnham, T. C., Dunlap, A., Stephens, D. W. 2015. Experimental evolution and economics. *SAGE Open*, 5(4).

Cassidy, J. 1996. The Decline of Economics. The New Yorker, 24 November 1996, pp. 50-60

Cazzolla Gatti R., Hordijk W., Kauffman, S. 2017. Biodiversity is autocatalytic. *Ecological Modelling*, 346:70-76

Cazzolla Gatti, R. 2011. Evolution is a cooperative process: the biodiversity-related niches differentiation theory (BNDT) can explain why. *Theoretical Biology Forum*, 104(1), 35-43

Cazzolla Gatti, R. 2016. Trends in human development and environmental protection. *International Journal of Environmental Studies*, 73(2), 268-276

Cazzolla Gatti, R., Fath B., Hordijk W., Kauffman S., Ulanowicz, R. 2018. Niche emergence as an autocatalytic process in the evolution of ecosystems. *Journal of Theoretical Biology* 454:110-117

Chamberlin, E. H. 1933. *The Theory of Monopolistic Competition*. Cambridge, Mass.: Harvard University Press

Clark, Gregory. 2001. "Farm Wages and Living Standards in the Industrial Revolution: England, 1670-1869," *The Economic History Review*, 54(3): 477-505

Clark, Gregory. 2005. "The Condition of the Working Class in England, 1209-2004," *Journal of Political Economy*, 113(6): 1307-1340

Conway, M. S. 2006. Darwin's dilemma: the realities of the Cambrian 'explosion'. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 361(1470), 1069-1083

Darwin, C. 1958. The Autobiography of Charles Darwin and Selected Letters. (edited by Francis Darwin) New York: Dover Publications, Inc.

Dave, T., Layton, A. 2019. Bio-inspired design for resilient water distribution networks. *Procedia CIRP*, 80, 275-280.

Debreu, G. 1974. Excess-demand functions. *J Math Econ*, 1:15–21

Debreu, Gerard. 1959. *Theory of Value*, New Haven and London: Yale University Press

Dixit, A. K., Stiglitz, J. E. 1977. Monopolistic Competition and Optimum Product Diversity *The American Economic Review*, 67(3): 297-308

Dobb, M. 1938. A note on some aspects of the economic theory of Marx. *Science & Society*, 2(3) pp. 322-331

Driffill, J., van der Ploeg, F. 1993. "Monopoly Unions and the Liberalisation of International Trade," *The Economic Journal*, 103(417): 379-385.

Durlauf, S. N. 2020. Institutions, Development, and Growth: Where Does Evidence Stand? In

Baland, J. M., Bourguignon, F., Platteau,J. P. Verdier, T. (eds.) The Handbook of Economic Development and Institutions, Princeton and Oxford: Princeton University Press, pp.189-217.

Easterlin, R. A. 2000. The Worldwide Standard of Living Since 1800. *Journal of Economic Perspectives*, 14(1): 7-26

Edelman, G. M., Gally, J. 2001. Degeneracy and complexity in biological systems," *Proceedings of the National Academy of Sciences of the United States of America* (PNAS), 98(24): 13763-13768.

Engerman, S. L. 1994. "Reflections on 'The Standard of Living Debate': New Arguments and New Evidence," in James, John A. and Mark Thomas (eds.) *Capitalism in Context: Essays on Economic Development and Cultural Change in Honor of R. M. Hartwell*. Chicago & London: The University of Chicago Press, pp. 50-79

Frazer, W. 1974. Crisis in Economic Theory: A Study of Monetary Policy, Analysis, and Economic Goals. Gainesville: University of Florida Press

Fullbrook, E, Ed. 2003. The Crisis in Economics: The Post-Autistic Movement: The First 600 Days. London: Routledge

Garud, R., Karnøe, P. 2003. Bricolage versus breakthrough: distributed and embedded agency in technology entrepreneurship. *Research Policy*, 32: 277-300

Griffin, E. 2018. Diets, Hunger and Living Standards During the British Industrial Revolution. *Past & Present*, 239(1): 71–111.

Haldane, J. B. S. 1956. Time in Biology. Science Progress, 44(175): 385-402.

Harmand, Sonia et al. 2015. 3.3-million-year-old stone tools from Lomekwi 3, West Turkana, Kenya. *Nature*, 521: 310-315

Hayek, F. A. 1948. "The Meaning of Competition," in his *Individualism and Economic Order*. Chicago: The University of Chicago Press.

Hayek, F.A. 1988. The Fatal Conceit: The Errors of Socialism, The Collected Works of F.A. Hayek (W. W. Bartley III, ed.). Chicago: University of Chicago Press

Hidalgo, Cesar A., B. Klinger, A. L. Barabási, R. Hausmann. 2007. The Product Space Conditions the Development of Nations. *Science*, 317: 482–487

Hirsch, M. D., Papadimitriou, C.H. and Vavsis, S.A. 1989. Exponential lower bounds for finding Brouwer fixed points, *Journal of Complexity*, 5: 379-416

Hodgson, G. 2007. "The Revival of Veblenian Institutional Economics," Journal of Economic Issues, 41(2): 324-340.

Hodgson, G., Knudsen, T. 2010. Darwin's Conjecture: The Search for General Principles of Social and Economic Evolution. *University of Chicago Press*

Hoover, K. 2016. The Crisis in Economic Theory: A Review Essay. *Journal of Economic Literature* 54(4): 1350-1361

Hordijk W. and Steel M. 2017. Chasing the tail: The emergence of autocatalytic networks. *BioSystems* 152:1-10

Hordijk W. and Steel M. 2018. Autocatalytic sets at the basis of life's origin and organization. *Life* 8:62

Hotelling, H. 1932 [1968]. Edgeworth's Taxation Paradox and the Nature of Supply and Demand Functions, *The Journal of Political Economy* 40(5): 577-616, reproduced in Baumol, William J. and Stephen M. Goldfeld, eds., *Precursors in Mathematical Economics: An Anthology*, London: The London School of Economics and Political Science, pp. 358-386

Hull, N. E. H. 1991. Networks & Bricolage: A Prolegomenon to a History of Twentieth-Century American Academic Jurisprudence. *The American Journal of Legal History*, 35(3): 307-322

Jacob, Francois. 1977. Evolution and Tinkering. *Science,* 196: 1161-1166.

Jacobs, J. 2000. *The Nature of Economies*. Vintage Books, 190 pp.

Jones, C. I. 2019. Paul Romer: Ideas, Nonrivalry, and Endogenous Growth, The Scandinavian Journal of Economics, forthcoming

Kantorovich, A. 1993. Scientific Discovery: Logic and Tinkering. Albany NY: SUNY Press

Kauffman S. 2016. Humanity in a Creative Universe. Oxford University Press.. N.Y.

Kauffman, S. 1988. The evolution of Economic Webs, in The Economy as an Evolving Complex Systems, (ed. Philip W. Anderson Kenneth J. Arrow) Volume 5. A Proceedings volume in the Santa Fe Institute Studies in the Sciences of Complexity. Addison Wesley N.Y.

Kauffman, S. 2000. Investigations, Oxford University Press,

Kauffman, S. 2008. Reinventing the Sacred, Basic Books N.Y.

Kauffman, S. 2019. World Beyond Physics. Oxford University Press, N.Y.

Keynes, J. M. 1921. *A Treatise on Probability*. Reprinted as Volume VIII of Moggridge, D. E. ed. *The Collected Writings of John Maynard Keynes*. New York: St. Martin's Press, 1973

Keynes, J. M. 1936. *The General Theory of Employment, Interest and Money*, London: Macmillan. Reprinted as Volume VII of Moggridge, D. E. ed. *The Collected Writings of John Maynard Keynes*. New York: St. Martin's Press

Kirzner, I. 1973. Competition and Entrepreneurship, Chicago, USA, University of Chicago Press.

Kirzner, I. 1982. Uncertainty, discovery, and human action: A study of the entrepreneurial profile in the Misesian system, in Israel Kirzner (ed), Method, Process, and Austrian Economics: Essays in Honor of Ludwig von Mises, Lexingtion, MA and Toronto, Lexington Books

Kirzner, I. 1997. Entrepreneurial discovery and the competitive market process: An Austrian approach, *Journal of Economic Literature*, 35, 60-85.

Kiss, T., Kiss, V.M. 2018. Ecology-related resilience in urban planning – A complex approach for Pécs (Hungary). *Ecological Economics* 144:160–170

Knight, F. 1921. Risk, Uncertainty and Profit. University of Chicago Press, Chicago.

Knorr, K. D. 1979. Tinkering toward Success: Prelude to a Theory of Scientific Practice. *Theory and Society*, 8(3): 347-376

Koppl, R. 2014. From Crisis to Confidence: Macroeconomics after the Crash, Hobart Paper 175, Institute of Economic Affairs, London

Koppl, R. 2017. Shocked Disbelief, in Doria, Francesco Antonio (ed.) *The Limits of Mathematical Modelling in the Social Sciences: The Significance of Gödel's Incompleteness Phenomenon*, World Scientific

Koppl, R., Harriot, J., Devereaux, A., Kauffman, S. 2018. A Simple Combinatorial Model of World Economic History. arXiv:1811.04502

Koppl, R., Kauffman, S., Felin, T., Longo, G. 2015. Economics for a creative world. *Journal of Institutional Economics*, 11(1): 1-31

Koppl, Roger. 2018. *Expert Failure*. New York and Cambridge: Cambridge University Press

Kristol I. & D. Bell (editors). 1980. *The Crisis in Economic Theory*. Special issue of *The Public Interest*

Kropotkin, P. 1902. *Mutual Aid: A Factor of Evolution*. New York: McClure Phillips & Co.

Laibman, D. 1997 Editorial Perspectives: In Defense of Economics. *Science & Society*, 61(2): 154-160

Law, J. 1705 [1966]. *Money and Trade Considered, With a Proposal For Supplying The Nation With Money*, New York: Augustus M. Kelley Publishers

Lenski, R. E., Burnham, T. C. 2018. Experimental evolution of bacteria across 60,000 generations, and what it might mean for economics and human decision-making. *Journal of Bioeconomics*, 20: 107-124.

Levine, J. M., HilleRisLambers, J. 2009. The importance of niches for the maintenance of species diversity. Nature 461(7261): 254-257.

Levi-Strauss, C. 1966. *The Savage Mind*, Chicago: The University of Chicago Press

Lietaer, B., R.E. Ulanowicz, Goerner, S.J., McLaren, N. 2010. Is our monetary structure a systemic cause for financial instability? Evidence and remedies from nature. *Journal of Futures Studies*, 14(3):89-108

Lowery, Y., Baumol, W. J. 2013. Rapid Invention, Slow Industrialization, and the Absent Innovative Entrepreneur in Medieval China. *Proceedings of the American Philosophical Society* 157: 1-21.

Mandeville, B. 1729 [1924]. *The Fable of the Bees: Or, Private Vices, Publick Benefits*, with a Commentary Critical, Historical, and Explanatory by F. B. Kaye, two volumes. Oxford at the Clarendon Press

Mantel, R. 1974. On the characterization of aggregate excess-demand. *J Econ Theory,* 7:348–353

Marx, K. 1904. Author's Preface. In *A Contribution to the Critique of Political Economy*, translated from the second German edition (1897) by N. I. Stone. Chicago: Charles H. Kerr & Company, pp. 9–15

Matsuyama, K. 1995. "Complementarities and Cumulative Processes in Models of Monopolistic Competition," *Journal of Economic Literature*, 33(2): 701-729.

Matutinović, I. 2002. Organizational patterns of economies: an ecological perspective. *Ecological Economics*, 40(3), 421-440

Matutinovic, I. 2005. The microeconomic foundations of business cycles: From institutions to autocatalytic networks. *Journal of Economic Issues*, 39(4):867-98

McCloskey, D. N. 2016. The great enrichment: A humanistic and social scientific account. *Scandinavian Economic History Review*, 64(1), 6–18

Menger, C. 1871 [1981] *Principles of Economics* translated by James Dingwell and Bert F. Hoselitz. New York and London: New York University Press

Meyer, P. N. 2014. Shaping Your Legal Storytelling: Voice and perspective can affect how the law is applied to the facts of your case. *ABA Journal*, 100(10): 26-27

Norris, K. S. 1993. *Dolphin Days: The Life and Times of the Spinner Dolphin*. New York and London: W. W. Norton & Company

O'Driscoll, G., Rizzo, M.. 1985. *The Economics of Time and Ignorance*, Oxford: Basil Blackwell

Ogburn, W. F. 1922. *Social Change With Respect to Culture and Original Nature*. New York: B. W. Huebsch, Inc.

Pak, S. (2004). The Biological Standard of Living in the Two Koreas. *Economics and Human Biology*, 2, 511–21

Panyam, V, Huang, H., Pinte, B. Davis, K., Layton, A., and Walker, J.M. 2019. Bio-Inspired Design for Robust Power Networks. In 2019 *IEEE Texas Power and Energy Conference (TPEC) IEEE*, pp. 1-6

Papadimitriou, C. H. 1994. On the complexity of the parity argument and other inefficient proofs of existence, *Journal of Computer and System Sciences*, 48: 498-532

Pasternak, R. E. 1964. Unemployment: a Crisis in Economic Theory, *Challenge*, 13(1): 17-19

Richardson, G. B. 1960. *Information and Investment: A study in the Working of the Competitive Economy*. Oxford: Oxford University Press

Richardson, G. B. 2003. Differentiation and continuity in the market economy. *Advances in Austrian Economics*, 6: 93-99

Richter, M. K., Wong, K. 1999. Non-computability of competitive equilibrium. *Economic Theory*, 14: 1-27

Risinger, M, Saks, M. J., Thompson, W. C., Rosenthal, R. 2002. The Daubert/Kumho implications of observer effects in forensic science: hidden problems of expectation and suggestion. *California Law Review*, 90(1): 1–56

Robinson, J. 1972. "The Second Crisis of Economic Theory," *The American Economic Review*, Vol. 62(1/2): 1-10

Robinson, J. 1933. *The Economics of Imperfect Competition*. London: Macmillan and Company, Limited.

Romer, P. 1990. "Endogenous Technological Change," *Journal of Political Economy*, 98 (5): S71–S102

Roser, M., Ortiz-Espina, E. 2017. Global extreme poverty (Our World in Data); https://ourworldindata.org/extreme-poverty/

Rubin, Paul. 2019. *The Capitalism Paradox: How Cooperation Enables Free Market Competition*. New York and Nashville: Post Hill Press.

Schumpeter, J. A., 1934, *The Theory of Economic Development*. Oxford University Press: Oxford

Schwekendiek, D. 2009. Height and Weight Differences between North and South Korea. *Journal of Biosocial Science*, 41(1), 51–5

Selgin, G., Lastrapes, W. D., White, L. H.. 2012. Has the Fed been a failure? *Journal of Macroeconomics*, 43(3): 569-596

Shackle, G.L.S. 1972. *Epistemics and Economics*. London: Cambridge University Press

Shipton, C. and Nielson, M. 2018. The Acquisition of Biface Knapping Skill in the Acheulean, in Di Paolo, Laura Desirèe, Fabio Di Vincnzo, and Francesca De Petrillo (eds.) *Evolution of Primate Social Cognition*, Springer, pp. 283-297

Sinclair, U.. 1994 [1934]. *I, Candidate for Governor: And How I Got Licked*. Berkeley, Los Angeles, London: University of California Press

Smets, F., Wouters, R. 2003. An estimated dynamic stochastic general equilibrium model. *Journal of the European Economic Association*, 1: 1123–75

Smith, A. 1776 [1789/1904/2000]. *An Inquiry into the Nature and Causes of the Wealth of Nations*, Library of Economics and Liberty, http://www.econlib.org/library/Smith/smWNCover.html, last visited 27 January 2012. (This online edition of the book is based on Edwin Cannan's 1904 compilation of the 5th edition, which was published in 1789.)

Sober, E., Wilson D. S. 2007. *Unto Others: The Evolution and Psychology of Unselfish Behavior*. Cambridge MA: Harvard University Press.

Solé, R. V., Ferrer-Cancho R., Montoya, J. M. Valverde, S. 2003. Selection, Tinkering, and Emergence in Complex Networks: Crossing the Land of Tinkering, *Complexity*, 8(1): 20-33.

Solow, R. M. 1956. A Contribution to the Theory of Economic Growth. *Quarterly Journal of Economics*, 70(1): 65–94

Sonnenschein, H. 1972. Market excess-demand functions. *Econometrica*, 40(3):549–563

Sonnenschein, H. 1973. Do Walras' identity and continuity characterize the class of community excess-demand functions? *Journal of Economic Theory*, 6:345–354

Steel, M., Hordijk, W., Kauffman, S. 2020. Dynamics of a birth-death process based on combinatorial innovation. *Journal of Theoretical Biology*, 491:110187

Stringer, Chris and Julia Galway-Witham. 2017. On the origin of our species. *Nature*, 546: 212-214

Thieme, H. 1997. Lower Palaeolithic hunting spears from Germany. *Nature*, 385: 807- 810.

Timmer, A. 2015. Judging Stereotypes: What the European Court of Human Rights Can Borrow from American and Canadian Equal Protection Law. *The American Journal of Comparative Law*, 63(1): 239-284

Ulanowicz, R.E. 1997. *Ecology, the Ascendent Perspective*. Columbia University Press. N.Y.

Ulanowicz, R.E. 2009. A Third Window: Natural Life beyond Newton and Darwin. Templeton Foundation Press.. Conshohocken, Pennsylvania

Ulanowicz, R.E. 2009. The dual nature of ecosystem dynamics. *Ecological Modelling* 220:1886-1892

Unattributed. 1920. Milestones in the development of the American passenger locomotive. *Scientific American*, 123(14): 329

Unattributed. 1921. Past and Present of American Railroading. *Scientific American*, 125(6): 99

Veblen, T. 1898. Why is economics not an evolutionary science? *Quarterly Journal of Economics*, 12(4): 373-397

Venables, A.J., Smith, A. 1986. Trade and Industrial Policy under Imperfect Competition, *Economic Policy*, 1(3): 621-672.

Walras, L. 1874-1877 [1954]. *Elements of Pure Economics*, translated from the Edition Définitive of 1926 by William Jaffé, Homewood, Ill.: Richard D. Irwin, Inc.

Weick, K. E. 1993. Organizational Redesigns As Improvisation, in Huber, George P. and William H. Glick (eds.) *Organizational Change and Redesign: Ideas and Insights for Improving Performance*, New York and Oxford: Oxford University Press, pp. 346-383

Weitzman, M. L. 1994. Monopolistic Competition with Endogenous Specialization. *The Review of Economic Studies*, 61(1): 45-56.

Wilkins, J., Schoville, B. J., Brown, K. S., Chazan M. 2012. Evidence of Early Hafted Hunting Technology. *Science,* 338(6109): 942-946

Wilson, D.S., Wilson, E.O. 2007. “Rethinking the theoretical foundation of sociobiology,” *The Quarterly Review of Biology*, 82(4): 327-348

Wisman, J. D. 1979. Toward a Humanist Reconstruction of Economic Science. *Journal of Economic Issues*, 13(1): 19-48

Young, A. A. 1928. Increasing Returns and Economic Progress. *Economic Journal*, 38(152): 527-542