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Challenges of Integrating Complexity and Evolution into Economics

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Abstract

Complex systems theory and evolutionary theory hold important insight for economics, yet to date they have played a limited role in shaping modern economic theory. This chapter reviews different notions of equilibrium and explores four distinct areas relevant to the incorporation of evolutionary and complexity ideas into economics, finance, and policy. It investigates the determinants of major economic transitions, such as the Industrial Revolution or the collapse of the Soviet Union. It asks whether evolutionary processes should lead to an increase in complexity, on average, of economic and social systems over time. It reviews modern theories of group learning in biology, which have both evolutionary and complexity dimensions, to see if they might be relevant to human social institutions, such as firms. It analyzes whether the structure of human interactions or individual human intelligence is primarily responsible for the performance of our institutions. Finally, it finds the methods of evolutionary analysis and of complex systems to be extremely useful in capturing the open-ended, evolving nature of an economy composed of interactive agents and suggests that these methods be used to create more realistic models of actual markets and economies.

Introduction

To a biologist trained in evolutionary thinking and cognizant of the kinds of far-reaching technological and institutional changes that occur in real economies, it might come as something of a surprise to learn that evolutionary notions play a relatively minor role in modern economic theorizing. An older tradition, largely due to Schumpeter (1934, 1942), argues for the importance of treating economic growth as the result of technological innovation—performed by

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entrepreneurs in Schumpeter's early work, and by large corporations according to his later work. Subsequently, a stream of evolutionary theorizing grew up on the boundaries of industrial organization in which the innovation process is conceived of as a stochastic return on research and development investments (Dosi and Freeman 1988; Dosi and Nelson 2010; Nelson and Winter 1982). While modern theories of economic growth have integrated Schumpeterian insights (e.g., Aghion and Howitt 1990, 1998), neoclassical models tend to treat the innovation process as a black box. As Dosi and Nelson (2010:52) indicate: "Explicit recognition of the evolutionary manners through which technological change proceeds has also profound implications for the way economists theorize about and analyze a number of topics central to the discipline." Yet, today we have no first principles *theory* for how or why economic innovation happens, although interesting formulations have been proposed (e.g., Weitzman 1998). Furthermore, evolutionary reasoning in other areas of economics, with the possible exception of finance (discussed further below), is largely absent.

The situation is similar for the emerging science of *complex systems* (e.g., Anderson et al. 1988; Kirman 2010; Miller and Page 2007; Arthur 2014). While much newer than evolutionary science, the strong affinity between the foundational ideas of complexity—bottom-up processes, multilevel phenomena, emergence—and certain traditional notions within economics—Adam Smith's "invisible hand," von Hayek's "spontaneous order," and the discipline's characteristic methodological individualism—would seem to make complex systems and evolution natural bedfellows, if not outright partners in the field of economics. Yet at present, complexity considerations are, like evolutionary concepts, on the fringes of academic economics. There are a variety of reasons for this state of affairs, some substantive (e.g., methodological), others perhaps more sociological. Consider, for example, the evolution of economic theory toward an axiomatic approach, one far removed from its earlier links with physics. This resulted in theorems becoming common in economic theory whereas they are uncommon in most analyses of complex systems.

What exactly would it take for economics to become more *evolutionary*? In biology, an evolutionary system possesses information (hereditary material) that interacts with the environment to achieve function (phenotype), and recombination and/or mutation produce variation in functional types. The resultant variation is maintained in a population; some of the variants survive and reproduce better than others (transmission), resulting in the corresponding hereditary material becoming more prevalent in future generations. Economic systems possess essentially all of these properties, from engineering designs and business plans (Beinhocker 2006)—the hereditary information—to populations growing and competing and subject to selection—think of start-up firms all trying to survive—and variation produced by "recombining" older ideas to produce new ones.

Evolutionary mechanisms are useful for exploring economic phenomena for several reasons. An evolutionary perspective offers a broader, more natural

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way to see and understand economic systems. There are many features natural to evolutionary systems that may not be obvious to economists in the absence of such a perspective. For instance, evolutionary processes are open-ended and can be viewed as parallel computations; the introduction of (modest) random change allows creativeness, and directed mutation often speeds up the process. Such systems can be effectively modeled on computers to allow behaviors to be explored even when they cannot be solved analytically. In this regard, agent-based models are often more realistic than simplified analytical models, typically at the expense of analytical tractability (cf. Epstein and Chelen, this volume). The antipathy of economists to such an approach is due mainly to the idea that the assumptions made in these models are "ad hoc." However, most of the assumptions made in theoretical economic models are also "ad hoc," introduced to facilitate the mathematical tractability at the expense of reality, but accepted because of their familiarity.

Although the evolutionary approach has played a role in the history of economic thought, that associated with complex systems is much less familiar. By *complex system* we mean one in which there are a number of components that interact directly with one another and indirectly via linked causal pathways, in such a way that it is difficult to determine, *ex ante*, by simply concentrating on the components, what the aggregate behavior of the overall system will be. Fluid mechanical turbulence (e.g., Frisch 1995) and John Conway's Game of Life (e.g., Gardner 1970) are two well-known examples of complex systems. It is conventional to distinguish complexity from *complication,* since the latter may arise in a system having relatively simple interactions, such as a linear system, but of high dimension. By *complex adaptive system* we further stipulate that the components have to be capable of adaptation to one another and/or to their environment; effectively, this requires memory. Since humans are highly adaptive we think of economies as complex adaptive systems. But this does not mean that the system will react in the same way as the individuals, or that the aggregate result will even be consistent with what the individuals are seeking. For example, Schelling's segregation model is often considered to be a complex adaptive system, where individuals act upon information regarding their local environments, but where the overall result, complete racial segregation, need not reflect the preferences of any individual (Schelling 1971).

Complex adaptive systems are not necessarily evolutionary but they can be. Such systems are defined by remembered information in the form of rules which define the system (environment) and strategies that define agents (or nodes) of the system. Change any of these rules or strategies and their interaction potentially changes the behavior of the system. Complexity scientists often try to understand the behaviors of complex systems and then explore how changes in the rules and strategies change system behaviors. When complex adaptive systems are evolutionary, selection can occur on at least two levels: at the level of individual agents or the whole system interacting with other systems. Even if the information defining the interaction of agents resides entirely

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in the agents, the level at which selection occurs can lead to profoundly different outcomes. For clarity, it is convenient to distinguish these systems and call situations where the strongest selection occurs at the level of the whole system CAS1, and systems in which the strongest selection responds to the local needs of agents as CAS2 (Wilson, this volume). If one wants to alter a system to achieve some particular predetermined outcome or behavior, then analyzing the consequences of any measure on the aggregate outcomes from an evolutionary perspective may be the most effective approach, but one must be careful about the level at which selection is occurring.

In contrast with evolutionary and complex systems perspectives, much of contemporary economic modeling is based on notions of Bayesian rationality and equilibrium. Incomplete information is modeled in great detail, but individuals are assumed to have deep knowledge of the signal structure on the basis of which they form and update beliefs. Furthermore, their beliefs and actions are coordinated and their plans are mutually consistent, requiring adjustment over time in response to exogenous shocks. Departures from rationality are explored typically as a robustness check on equilibrium predictions, and to obtain more plausible equilibria, for instance, in models of entry deterrence, the iterated prisoners' dilemma, the centipede game, bargaining, or asset price bubbles (Abreu and Brunnermeier 2003; Abreu and Gul 2000; Kreps et al. 1982; McKelvey and Palfrey 1992; Milgrom and Roberts 1982). There is also a vibrant and rapidly growing literature in behavioral and experimental economics that is more methodologically agnostic, but this has not yet made much of an impact on standard textbook treatments of the core theory (e.g., Mas-Colell et al. 1995; for further discussion, see Burnham et al., this volume). In addition, firm behavior continues to be treated as profit-maximizing in standard accounts, to the neglect of organizational and other theories (Currie et al., this volume).

While any list of the key differences between conventional models and an alternative approach is bound to be approximate, Table 5.1 identifies some key differences.

Much research in economics involves elements from the rightmost column. From other-regarding preferences (e.g., Aaron 1994; Cooper and Kagel 2013), to social networks (e.g., Goyal 2009; Jackson 2010; Ioannides 2012), heterogeneous agent macro (e.g., Guvenen 2011; Heathcote et al. 2009), and the emergence of self-governance (e.g., Ostrom 1990, 2005), much is known about models in which particular boxes on the right are activated, holding everything else to the well-understood baseline specifications of the center column. Less understood is what happens when a researcher makes many boxes in the right column active, for example, when preferences can evolve, social networks are active, prices are heterogeneous, and selection is working on multiple levels. Clearly, we should not expect, at this point, to activate everything in the right column and hope to make much sense of model output. However, to move in the direction indicated by the evolutionary, complexity-theoretic elements on

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Table 5.1 Contrasting perspectives on economic theory and models.

Economic conception	Conventional representation	Complex, evolutionary approach
Number of agents	Representative (one, few)	Many (possibly full-scale)
Diversity of agents	Homogeneous or few types	Heterogeneous, possibly all unique
Agent goals, objectives	Scalar-valued utility, fixed	Other-regarding, evolving
Agent behavior	Rational, maximizing, brittle	Purposive, adaptive, behavioral
Learning	Individual, social	Empirically grounded, group
Information	Centralized, free, uncertain	Distributed, costly, tacit
Beliefs	Coordinated for free	Uncoordinated, costly to coordinate
Interaction topology	Equal probability, well-mixed	Social networks
Markets	Walrasian, single price vector	Decentralized, local prices
Firms and institutions	Absent or unitary actors	Multi-agent groups
Selection operators	Single level	Multilevel
Governance	Median voter	Self-governance, rule evolution
Temporal structure	Static or equilibrium dynamics	Disequilibrium dynamics
Source of dynamism	Exogenous, outside economy	Endogenous to the economy
Properties of dynamics	Smooth, differentiable	Irregular, volatile
Character of dynamics	Markovian, path is forgotten	Path-dependent, history matters
Solution concepts	Equilibrium at the agent level	Macro steady-states (stationarity)
Multilevel character	Neglected, fallacy of division	Intrinsic, macro-level emerges
Methodology	Deductive, mathematical	Abductive, computational
Ontology	Representative agent	Ecology of interacting agents
Data	Samples, aggregate	Micro-data, Big Data
Policy stance	Designed from the top down	Evolved from the bottom up

the right is desirable, and even necessary, for progress in economics. Transition to a less stylized, empirically deeper representation of economic, financial, and policy processes is inherently a move to a more evolutionary and complexity theoretic perspective.

In seeking to represent economic and financial processes using evolutionary and complex adaptive system frameworks, the kinds of models that result will be constrained, but in different ways to the constraints found in standard economic models. This will provide discipline to such modeling efforts and will not amount, as sometimes suggested, to a foray into the wilderness of ad hoc assumptions. Descriptively, we look for behavioral or institutional rules that have survived evolutionarily. Normatively, we attempt to synthesize such rules that provide a selective evolutionary advantage.

In many ways social, economic, and financial processes are quite different from biology. They feature forward-looking agents, meaning that more often than not "mutation" processes (i.e., change mechanisms in play) are directed. This distinction is far from simple; prediction is often based on the extrapolation of the past to the future. Thus, the squirrel that stores food does not, in the usual sense, anticipate its needs in the future; the mapping from past experience to a tendency to store is the behavior which is selected. Hence the squirrel

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acts as if it anticipates its future needs. For human agents, planning may be conscious whereas biological ones are more reactive/myopic even though evolution may lead them to behave similarly.

Notions of equilibrium used by biologists and economists are quite different. For example:

1. Thermodynamic equilibrium is the most restrictive definition: All observable variables are constant and, in addition, all fluxes of individual steps in a network have to vanish as expressed by the principle of detailed balance.
2. The notion of equilibrium used in mathematical biology, in particular in the theory of dynamical systems, concerns only vanishing changes in variables and is more general than thermodynamic equilibrium.
3. The concept of equilibrium in economics refers to situations where economic forces are balanced, such that the economic variables will not change unless external influences perturb the system. A standard example is market clearing, where supply equals demand. This refers to a static notion more akin to mechanical equilibrium in physics. Economists have been unable to prove theoretically that markets, which are not in equilibrium, will converge to an equilibrium (e.g., Fisher 2011) and have been obliged to discuss the properties of the equilibrium state and not how it is achieved.
4. In a strict sense, nothing on Earth can be at equilibrium because of permanent incoming and outgoing radiation of different temperatures. The notion of quasi-equilibrium, nevertheless, is very useful to describe processes which take place on different timescales.
5. Quasi-equilibrium, as used in mathematical biology, requires two processes with sufficiently different time constants. The fast process converges to the so-called center manifold and moves slowly on it and this has been used in economics to study situations in which prices and quantities change at very different speeds (Blad and Kirman 1985). A variant of quasi-equilibrium occurs in some stochastic processes, which converge to and fluctuate around a state until they eventually end up in an absorbing state that may be very different.

In what follows, we investigate four distinct areas relevant to the incorporation of evolutionary and complexity ideas into economics, finance, and policy. First, we investigate the determinants of major economic transitions, such as the Industrial Revolution (Allen 2009) or the collapse of the Soviet Union (Lohmann 1994). Second, we ask whether evolutionary processes should lead to an increase in complexity, on average, of economic and social systems over time. Third, we take a look at modern theories of group learning in biology, which have both evolutionary and complexity dimensions, to see if they might be relevant to human social institutions, such as firms. Finally, we study the question of whether it is the structure of human interactions that are most

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responsible for the performance of our institutions, or if individual human intelligence is essentially responsible.

Major Transitions in Biological and Economic Systems

We have argued that ideas from complex systems theory and evolutionary theory are very important for economics. As a first illustration, we compare the determinants and consequences of major transitions in biological and economic systems to highlight some key similarities and differences.

To set the stage, we first need to specify what is meant by "major transitions." We define major transitions as large-scale structural and functional changes in biological systems and "revolutionary" technological changes in economies. Examples from biology and economics are the transition from prokaryotic life to the eukaryotic cell and the Industrial Revolution, respectively.

What are the determinants of these major transitions? Were they driven by conditions of abundance or scarcity? In biology, major transitions require a substantial increase in internal functional and regulatory capabilities of organisms. Similarly, technological transitions depend on major investments in infrastructure and organization. These large investments are possible only when new resources become available or an existing one becomes exploitable, and is abundant or fairly cheap. Biological examples are the oxygen-based metabolism that produces several times more energy than fermentation or the release of unexploited resources due to mass extinction. In biological systems, it is unknown to what extent major innovations result from scarcity, but examples do exist (Spriggs et al. 2014). Things are less clear in economic systems, in particular because abundance and scarcity are endogenous—major transitions are required to create resource abundance in the first place. Furthermore, in times of crisis, deficit spending is often used to offset the consequences and mobilize resources that have become inactive, something which does not have an obvious biological analogy. So causality runs both ways.

Here we focus on major technological changes rather than on economic crises in general. However, it is worth noting that in the past considerable technological progress was made when increased military expenditure inadvertently led the way out of a crisis, as happened before the Second World War. While this endogeneity issue might, at least to a certain extent, be present in biological transitions as well, economic systems display certain additional features that are either not observed in biology or are found in a restricted number of biological systems. For example:

1. Resources in economic systems are allocated through conscious direction, either through the financial system or the public sector. Even in conditions of general scarcity, certain entities may have access to abundant resources. Similarly, resources may be generally abundant but unavailable to most entities.

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2. Investments in technological innovations depend on beliefs about future profitability. Major transitions may be associated with wildly optimistic expectations about a promising innovation (e.g., railways or Internet commerce). The resulting speculative boom and bust can redistribute wealth but can also leave behind an infrastructure that is essential for sustained growth in subsequent years.
3. Many of the most recent technological innovations have been achieved through large (mainly public) investments in specific areas (Mazzucato 2013a). While private sector financing is based on expectations of profitability, public sector resource direction is less well understood. Some initiatives may be easy to finance through the public sector because they capture the imagination of the general public, or because they can be justified in the name of national security. Many major innovations have been associated with the defense department in the United States.
4. The role of path dependence and accumulation: Empirical evidence suggests that big technological changes are clustered in time. It is difficult to conceive of a similar clustering in biological systems.

Turning toward the effects of major transitions, a clear parallel between biology and economics (consistent with evolutionary science) is observed in situations where the strength of selection is being either increased or reduced. When a new opportunity arises, species diversity increases or new firms proliferate, respectively. In biology, examples follow every mass extinction in the fossil record, as well as after the introduction of oxygen in the atmosphere. Examples in economics are the Internet, the availability of cheap liquid fuel (distilled petroleum), and the idea that proper organization of division of labor can result in far less expensive products. This explosion of diversity leads to a "filling up" of the opportunity space. Increased competition serves as a selection mechanism and, as a result, diversity decreases as some species go extinct. It seems likely that technological innovations exhibit similar regularities: a great variety of prototype solutions to the new technical problems appears almost instantaneously after a new resource has been introduced, but most of them are abandoned and eventually, only a few remain (Klepper 1996; Klepper and Simons 1997).

Overall, more research is needed to understand the determinants of large-scale economic transitions. Taking an evolutionary approach should lead to substantial progress in that direction.

Growth of Complexity

The previous discussion relates to the prediction that new opportunity begets diversity, but does this translate into sustained increases in the complexity of economic systems? Before considering this, it is useful to recast the basic

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ingredients of the evolutionary process for economics. As discussed above, there are considerable differences in how variation is generated and selection acts upon this variation in biology and economics: the latter has the capacity to be forward looking and able to sort ideas before they are manifested as changes in strategies or product lines. This highlights difficulties in the distinction between the genotype and phenotype in economics. Analogous to the biological genotype, the "econotype" includes (often secretive) features such as strategies, structural organization, and rules. These interact with the environment to produce the actual interfaces (i.e., the phenotype) with other agents or firms, including support, advertising, products, and image. Similar to genotypes in biology, partial or entire econotypes are transmitted during the establishment of new firms or when strategies, for example, are copied by other existing firms. This creates selective evolution if competition results from the accelerated growth of firms using the new strategy, compared to those that do not. To measure economic evolution requires (a) the identification of a set of strategies (i.e., variants in the econotype); (b) apportionment of strategy types to, for example, different firms; (c) tracking these firms/econotypes over time to observe whether they shrink, disappear, or grow, or merge; (d) identifying the new firms or strategies that emerge.

As in other systems, complexity in economics can be understood as information and, in particular, the way this information is embodied in the network of shared norms and institutions. Although some degree of unification exists (Gell-Mann and Lloyd 2003), complexity can be measured in numerous ways (Lloyd 2001), and one of the challenges to understanding different scales and sectors of the economy is to identify which of these measures are most informative. All this presupposes that we have accurate models that can scale up from micro to meso and finally macro phenomena, while accounting for the effects of the most aggregated upper levels on more distributed sublevels. Whether or not these effects, or feedbacks, are positive or negative will play an important role in the dynamics of the system. Complexity, in this sense, emerges as differentiation in structures and behaviors at all three levels. In particular, differentiation (as a proxy for information and therefore a component of overall complexity) may be sectoral (economic sector), functional (e.g., the number of departments in a firm), or be based on social position or wealth.

How may evolution help us understand complexity, and does evolution necessarily (or ever) lead to increases in complexity? This question is rarely asked in economics, and to our knowledge there is no general theory for how evolution should lead to increased or decreased complexity in economic systems. For a discussion of the issue at a general level, the reader is referred to Mayfield (2013). Here we limit ourselves to biological analogy to make some basic predictions.

The most parsimonious explanation for changes in economic complexity is that it has nothing to do with an evolutionary process based on selection for efficiency, performance, etc. That is, the addition, modification, or loss of norms

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or institutions may not be linked to competition, as when family-operated firms simply shut down due to the retirement of its owners. Assuming that evolution of econotypes does occur, it is expected to lead to increases in complexity whenever increased complexity provides better performance. For example, Auerbach and Bongard (2014) showed that adaptation of virtual machines to complex, changing environments mediated the evolution of more complex structures and strategies. In economic systems, a similar phenomenon would be expected, for instance, following a major innovation or creation of a new product niche, whereby firms need to create supply links, production lines, etc. However, when a product requires refinement, this usually means adding modules that correct mistakes, inefficiencies, etc. Thus, complex, changing environments (e.g., markets) should result in increased complexity, but this would be a net effect; some refinements could involve simplification as a necessity due, for example, to limitations or costs in maintaining suboptimal or less adapted features (e.g., strategies). Moreover, if the environment itself were to become more simple or predictable (e.g., if evolution through complexification has effectively solved many market challenges), we would expect simplifications to occur. These could be, for example, in the form of downsizing workforces or increased structural efficiencies. More routinely, the basic expectation is cycles or periods:

$$\text{Simple} \rightarrow \text{Complexify} \rightarrow \text{Complex} \rightarrow \text{Simplify} \rightarrow \text{Simple}$$

where each subsequent "simple" state is more complex than the last. This leads to the expectation that over *sufficiently long periods* there would be a net increase in complexity.

Complexifying or simplifying by adapting to adverse external conditions and/or self-regarding assessments of declining productivity is more likely to occur and be successful if there are additional adaptations in flexibility. Indeed, flexibility can be viewed as an evolutionary innovation in itself (Sol et al. 2002). The analog of flexibility at a given economic level is "plasticity" in biological systems (Fusco and Minelli 2010). The plastic trait and its components (trigger points and behavioral change) are adaptations to environmental change and may take many generations to achieve by natural selection (Lande 2009). The interesting question for economies is the extent to which a culture of flexibility becomes the norm, where structures can be seamlessly modified or supplanted. Flexibility is likely to be complex itself, especially at the meso level (e.g., market sector), since it can take on different forms for different characteristics of a firm. Firms can maintain their presence at the technological frontier by either investing in research and development or buying new technology, or doing these activities in specific combinations. All firms make such trade-offs, but possibly do not realize the challenges of flexible change. Because flexibility often involves modifying or shedding, this could destabilize workforces, and these trade-offs need to be taken into consideration when evaluating the benefits of flexibility.

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A final, important facet of complexity regards structures and substructures, which can be described as a network of information flow between components that ultimately influences the performance of the whole. This relates to major transitions as well as multilevel selection. The basic take-home message is that competition for performance between individuals within a group can lead to lower performance of the group as a whole. In contrast, when individuals relinquish their selfish strategies and cooperate and coordinate, the "whole" (e.g., firm) competes better. This is an important insight, not only because it provides expectations as to what will happen at the micro and meso levels; it suggests that the meso competitive environments themselves are subsets of larger (e.g., markets, regional, national) economies. This is because top-down rules and regulations do not align a given level (e.g., firms) in the same way that that level aligns its individual components (e.g., workers): as a result, the higher levels will experience internal conflict and therefore be suboptimal (i.e., inefficient and lower productivity). In a nutshell, inter-firm competition can align the interests and behaviors of the workforce, but there is no higher level of individuality that aligns the interests of different firms. Thus, firms will continue to compete for market share, with some having more successful econotypes than others, and thus tend to prevail. It is an open question in both biology and economics as to whether the evolution to internal coordination and efficiency at the meso level should increase or decrease complexity at this level, or at lower or higher levels.

Collective Learning

The acquisition and utilization of social information among potentially competing agents (e.g., between individuals within a firm, or among firms) are of central importance to economics. These processes influence how information from uncertain sources is perceived as well as collective decision making, learning, and the spread of knowledge or strategies. Beginning with the work of DeGroot (1974) there is now a rich literature on this topic, including the process by which learning occurs on interaction networks (Golub and Jackson 2010) and the propagation of beliefs, strategies, and misinformation (Acemoglu et al. 2010). For example, Acemoglu, Dahleh, et al. (2011) study the (perfect Bayesian) equilibrium of a learning model in social networks. Individuals can base decisions on a noisy environmental cue, related to the underlying state of the world, as well as on the past actions of other agents. They show the conditions under which such agents will asymptotically achieve accurate collective decisions as long as their observations are expanding, and thus agents can approximate the informativeness of incoming social cues. They also observe that if there are "excessively influential agents/leaders" (as defined by the underlying network topology), observations will not expand. It is important to note,

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however, that when agents have limited or "bounded beliefs," herding may occur and the "correct" action will not be taken by the group.

The Evolution of Conformist Bias and Informational Cascades

While it is possible to find, in the above models, the optimal weighting by which individuals should balance personal and social information (which depends on various factors such as the number of agents, the error distribution in estimates, and so on), deeper insight can be gained by considering the degree to which individuals are selfish (in the biological sense) or self-regarding. For example if individuals are purely selfish/competitive agents who seek to optimize their own payoffs, then it is informative to seek the evolutionary stable strategy/Nash equilibria of the decision-making system. In the context of social learning, Perreault et al. (2012) modeled the evolution of social learning in populations, assuming that individuals weigh information optimally according to Bayes' rule such that the reliance on external (environmental) cues predicts fitness-related contingencies. Additionally, the psychology employed by individuals, with which they bias behavior according to the perceived actions of others, also evolved. The evolutionary stable strategy was found in a wide range of environments to result in individuals adopting a conformist bias (i.e., they evolved an overreliance on social information). Together with previous work (e.g., Boyd and Richerson 1985), these results suggest that conformist bias may be a common, and perhaps universal, feature of social learning.

Similarly, Torney et al. (2015) found, when considering collective decision making among rational (Bayesian optimal) agents, that selection would result in these selfish agents becoming overreliant on social information, thereby producing a conflict between individual and collective self-interest. This, in turn, results in a suboptimal system that is poised on the cusp of total unresponsiveness resulting from rapid, socially reinforced transitions (maladaptive informational cascades).

Such results suggest that competition among agents, while often allowing improvement in decision making and learning (although rarely close to optimal), also risks sudden cascading failures. While improving performance in the short term, competition can result in system-wide fragility. Consequently, if the objective is to avoid sudden collapse and to achieve improved informational properties at both the individual and system levels, it is often important to regulate incentive structures such that agents do not simply adopt a purely competitive strategy. However, it is not clear whether it would be possible, or even desirable, to generate incentive structures such that all agents strive to achieve a common good. It is possible that the desired strategy which maximizes robustness and adaptability of complex adaptive systems may often be a balance of competition and cooperation, since a purely cooperative strategy may also result in conformity and lack of diversity in behavior/strategies.

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In addition to the incentives to individuals, it is also likely that the structure of the network by which social information is transmitted among agents will be important.

Correlated Information, Complex Environments, and the Wisdom of Crowds

The conventional view of the "wisdom of crowds," popularized by Surowecki (2004) and dating back to Condorcet's 1785 "jury theorem," relates to the pooling of diverse, but imprecise individual estimates. Accordingly, errors of judgment tend to cancel out when imperfect estimates are pooled into a consensus choice. Thus, it is expected that accuracy increases asymptotically as the number of decision makers increases. While a useful formulation, the standard "wisdom of crowds" relies on two, potentially unrealistic assumptions: (a) individual's estimates are uncorrelated and (b) individuals all have access to the same, single environmental cue. If these assumptions are relaxed (the argument being that in most real environments, cues exhibit some form of spatial and/or temporal correlation, and that there may be multiple environmental cues), our view of how collective intelligence is achieved is substantially changed. For example, using a simple model representing how animal groups may benefit from pooling information, Kao and Couzin (2014) showed that in only a minority of environments will we observe the traditional wisdom of crowds, and that when not observed, small or intermediate-sized groups maximize decision-making accuracy. The reason for this is the noise inherent in small groups, which allows individuals to avoid the detrimental effects of correlated information yet to maintain some of the benefits of group decision making.

Consequently, in many real-world scenarios, decision making may be optimized by small groups of interacting decision makers, and, for large organizations/groups, a modular decision-making structure may prevent overreliance on highly correlated information, thus again avoiding maladaptive informational cascades.

These rich results from biology, which have both evolutionary and complexity aspects, seem ripe for application in economics, financial and public policy systems.

Economic Performance: Institutional Structure or Individual Intelligence?

Whether economic agents are rational (*Homo economicus*) or instead follow simple heuristics is a topic of much debate among economists (see Burnham et al., this volume). In this section, we try to deflate this debate by pointing out that perhaps something quite different may be decisive for the economic outcome, namely, the institutional structure. To illustrate this claim, imagine

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that you have built a road between two towns and that this is the only road available; you would expect that the traffic between these two towns follows the path of this road, irrespective of the drivers' attributes. Thus, the question whether the drivers on the road are rational or not is only of secondary importance for the outcome. The following examples make a similar point in the domain of economics.

Example 1: Becker (1962)

Consider a simple decision problem in which a consumer can spend his income on two consumption goods. The prices of the two goods and the consumer's income will determine his choice set, called the budget set. Suppose now that there are many identical consumers who randomly, from a uniform distribution, choose a point on the budget set. This results in a distribution of demands on the budget set, with average demand being the midpoint of the budget set. As prices are varied, this will generate the classic downward sloping demand function. That is, the average of individuals' demands satisfy the *Law of Demand.* Note that this average demand can equivalently be determined by a single consumer who maximizes a simple utility function (e.g., a logarithmic utility with equal weights for the two goods). Becker's example depends on the fact that there are two goods, that the random draws are from a uniform distribution, and that consumers are never satiated. As Hildenbrand (1994) points out, this is highly restrictive. This simple example has been substantially generalized by Birchenall (2014).

Example 2: Gode and Sunder (1993)

Consider a set of traders who can buy or sell a certain asset on a double auction. Some traders are buyers, others are sellers. Buyers can resell the asset at a certain value. Sellers incur a cost for producing the asset. The traders' payoffs are the differences between the price at which they contracted and their resale value or the costs, respectively. If all traders were rational, the distribution of resale prices and costs determines the demand and supply functions. The market equilibrium is determined by the intersection of these two curves. But the same market outcome is also determined if all traders choose randomly in an interval between the lowest price at which any trader would sell and the highest price that any buyer would offer. Thus, the economic outcome with irrational or "zero intelligence" traders would seem to be the same as that with rational traders. Note, however, that in the case of the random choices, although the last trade or trades take place at the "equilibrium" price, the other trades take place at different prices. Therefore, in one case there will be a unique price at which goods are exchanged while in the other, different transactions at different prices converge to the equilibrium.

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Example 3: Evstigneev, Hens, and Schenk-Hoppe (2009)

Consider a set of dividend-paying assets. How can their prices be determined? The rational model assumes a single agent who maximizes intertemporal expected utility. This agent will then price these assets according to the contribution their dividends make to the agent's consumption stream. Now suppose a set of trading strategies can allocate wealth between these assets. Following the evolution of wealth, one sees that eventually the agent puts all the weight on the strategy that invests proportional to the expected relative dividends. In the limit, the resulting asset prices are equivalent to a simple model with a logarithmic utility function. Again, rationality is irrelevant for the outcome.

In general, the simplification of modeling the outcome of complex adaptive systems as if a single rational agent (Constantinides 1982) determines the economic outcome is very dangerous because it ignores the underlying dynamics. In finance, this is well known. In retrospect, asset prices can be described as if they were determined by a single optimizing agent; however, this model is not able to make predictions of asset returns. To the contrary, the more optimization is needed in matching the past, the worse the future performance of the investment rule. Simple robust principles like diversification and rebalancing are more successful than optimization (DeMiguel et al. 2009).

Individual or Collective Rationality?

Each of these examples suggests that it is the organization of the system rather than optimization by individuals which leads to "coherent" if not optimal outcomes. However, economists are often reluctant to abandon the hypothesis of individual rationality. Thus when faced with a choice between a model which explains aggregate outcomes as arising from underlying individual optimization and one in which the aggregate result did not arise from any such behavior they prefer the former. The argument would then be that the rationality hypothesis should be seen as an "as-if hypothesis." Similarly, modeling someone riding a bicycle or catching a ball can be thought of *as if* this person solves differential equations. Certainly this cannot be taken seriously as a description of the observed behavior. A more realistic view is that in many cases individuals do not consciously optimize but achieve the equivalent behavior through evolutionary selection, or through a process of learning. As Lucas (1986:S401) stated:

> In general terms, we view or model an individual as a collection of decision rules (rules that dictate the action to be taken in given situations), and a set of preferences used to evaluate the outcomes arising from particular situation-action combinations. These decision rules are continuously under review and revision; new decision rules are tried and tested against experience, and rules that produce desirable outcomes supplant those that do not.

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Yet this reasoning is not wholly convincing since while the sort of learning process involved can be shown to converge when individuals are learning about some exogenous process there is no reason to believe that it will do so when the environment itself is, at least in part, composed of other individuals who are also learning.

The question, then, is whether these examples in which aggregate outcomes are not the result of individuals maximizing are exceptions or symptomatic of a more general principle which suggests that we do not need to impose the strict assumptions of economic rationality on individuals in order to guarantee coherent and coordinated aggregate behavior. Such a principle has been found to apply in various other settings, including prediction markets or the Marseille fish market (cf. Kirman and Vriend 2001). In addition, many results in evolutionary game theory show that replicator dynamics (which can be interpreted as evolutionary selection, although again the distinction between an evolutionary process and a learning process has to be made clear) can lead to Nash equilibria (which are the ultimate outcome of rationality in games). Finally, as Padgett and Powell (2012) argue, the history of the Medici shows that a robust positioning of the family in the economy was more important than a maximization of expected payoffs (see also Padgett, this volume). This resembles the main theme of Gigerenzer et al. (2000): "Heuristics can make you smart." Changing the rules of markets changes the market outcome considerably. Thus, the organizational structure of the economic situation in question, matters more than the details of the behavior of the individuals in that situation.

But, if this is true, why are economists so reluctant to give up models based on optimizing individuals. The reason is quite simple. Conventional economics established a firm foothold because it is based on mathematical methods that were taught to graduate students, who then produced thousands of papers reinforcing the ideas that lay behind what had become the mainstream models. Yet, other methods exist to help formalize a less restrictive and more realistic view of the economy, that is as a complex system which is operated on by evolutionary processes. We hope that young scholars will use them to expand the repertoire of theoretical tools employed within the economics profession.

One technique used to gain some intuition about complex adaptive systems is to simulate them on a computer. This approach has already proven fertile in evolutionary finance (see, e.g., Brock and Hommes 1997; Hens and Schenk-Hoppé 2009; Lebaron 2006; Lo 2004; Lux 1995; Sethi 1996). Since simulation models cannot be easily verified by referees, it is very important to incorporate robustness checks and make the intuitive basis of the mode clearly. Mathematical methods that allow one to prove theorems in complex dynamic systems and evolution are models of statistical mechanics (e.g., Uffink 2007) and random dynamical systems (Arnold 1998). In addition, the *Agent_Zero* framework offers an agent-based computational model that permits many interesting features of complex dynamic systems and evolution to be modeled (see Epstein and Chelen, this volume; Epstein 2013).

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Conclusion

In an 1898 essay, Thorstein Veblen asked: "Why is Economics not an evolutionary science?" This question remains surprisingly relevant today. Veblen (1898/1998) distinguished between *teleological* and *evolutionary* modes of scientific thought, arguing that the economics of his day was built on the former approach because of a presumption that the economy is propelled toward a state of normalcy or equilibrium (Argyrous and Sethi 1996). Veblen was not alone; a number of leading economists, such as Marshall and Schumpeter, argued that economics has more to learn from biology than from the physics on which its formal structure is based. Despite these admonitions, economics has become a discipline in which the theory is constructed on the basis of an axiomatic mathematical approach epitomized by Bourbaki, rather than on either a biological-evolutionary view or one more related to the modern physics embodied in the complex systems approach.

We suggest that taking account of evolutionary processes operating on complex systems will enhance our understanding of the overall functioning of the economy.

Different notions of equilibrium exist in both evolving biological systems and their complex counterparts. The attachment of economists to an essentially static view of equilibrium is almost orthogonal to the notions that prevail in biology and complex systems.

Major transitions, normally attributed to exogenous shocks in modern macroeconomic models, are an integral part of the dynamics of both evolving biological and complex systems. How collective learning takes place is something that cannot be fully understood if the existence of heterogeneous interacting individuals is ignored, and the presence of informational contagion and informational cascades finds a natural explanation in the analysis of complex systems.

Information plays a central role in economics, a role which again fits naturally into the frameworks that we are recommending. In the examples presented here, the aggregate outcomes in a market or an economy could be equally well attributed to the structure of the system or to the behavior of the individuals within it. The former view attributes much less knowledge and reasoning capacity to the participants and allows one to model agents as using simple rules and adapting to their environment rather than as the omniscient individuals common to economic and particularly macroeconomic models.

We find that the methods of evolutionary analysis and of complex systems will be extremely useful in capturing the open-ended, evolving nature of an economy composed of interactive agents. Utilizing these methods will permit us to progress to more realistic models with simple individuals whose interaction leads to the often complicated and unstable dynamics that actually characterize real-world markets and economies.

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