Review of Political Economy

ISSN: 0953-8259 (Print) 1465-3982 (Online) Journal homepage: http://www.tandfonline.com/loi/crpe20

The Complexity Era in Economics

Richard P.F. Holt , J. Barkley Rosser Jr. & David Colander

To cite this article: Richard P.F. Holt , J. Barkley Rosser Jr. & David Colander (2011) The Complexity Era in Economics, Review of Political Economy, 23:3, 357-369, DOI: 10.1080/09538259.2011.583820

To link to this article: https://doi.org/10.1080/09538259.2011.583820

Published online: 24 Jun 2011.

Review of Political Economy,
Volume 23, Number 3, 357–369, July 2011

The Complexity Era in Economics

RICHARD P.F. HOLT*, J. BARKLEY ROSSER, JR.** & DAVID COLANDER†

*Economics Department, Southern Oregon University, Ashland, OR, USA;
**Economics Department, James Madison University, Harrisonburg, VA, USA;
†Economics Department, Middlebury College, Middlebury, VT, USA

ABSTRACT *This article argues that the neoclassical era in economics has ended and is being replaced by a new era. What best characterizes the new era is its acceptance that the economy is complex, and thus that it might be called the complexity era. The complexity era has not arrived through a revolution. Instead, it has evolved out of the many strains of neoclassical work, along with work done by less orthodox mainstream and heterodox economists. It is only in its beginning stages. The article discusses the work that is forming the foundation of the complexity era, and how that work will likely change the way in which we understand economic phenomena and the economics profession.*

1. Introduction

The neoclassical era in economics has ended and has been replaced by an unnamed era.[1] What best characterizes this new era is its acceptance that the economy is complex; thus it might be called 'the complexity era.' The complexity era has not arrived through a revolution. Instead, it has evolved out of the many strains of neoclassical work, along with work by less orthodox mainstream and heterodox economists. It is only in its beginning stages, but in our view, is the wave of the future. This article provides our sense of the work forming the foundation of the complexity era, and the way it will likely change how we understand economic phenomena and the economics profession.

2. The Future of Economics

Imagine for a moment that we were looking at the economics profession in England in 1890. One would say that Alfred Marshall, with his blend of historical

Correspondence Address: Richard P.F. Holt, Economics Department, Southern Oregon University, Ashland, Oregon 97520, USA. Email: rholt@sou.edu

[1]This article is based on material from our recent book (Rosser *et al.*, 2010). The argument that we present is an extension of our earlier book and article (Colander *et al.*, 2004a, 2004b).

ISSN 0953-8259 print/ISSN 1465-3982 online/11/030357–13 © 2011 Taylor & Francis
DOI: 10.1080/09538259.2011.583820

and analytical economics, was the economics of the future; Walras and Edgeworth, both of whom adopted a more mathematical approach, would be considered minor players. Now fast forward to the 1930s—in the area of cutting edge work Marshall is seen as a minor player, while the mathematical approach of Walras and Edgeworth has become the foundation for Samuelson's (1937) cutting-edge economics (although Marshall continues to be cited). Now fast forward 40–50 years again; imagine economics in the 2050s. Much of what is currently done in economics will not be cited or even considered important. Some parts of economics, which today are considered minor, will be seen as the forerunners of what economics will become.

The point of this comparison is to make clear that to judge the relevance of economic contributions one must be forward-looking. One needs a vision of what economics will be in the future. Current journal publication and citation metrics don't do that; they are backward looking, and thus encourage researchers to continue research methods and approaches of the past, rather than developing approaches of the future. They are useful, because they show current activity, but this is only part of the picture. Articles dotting 'i's and crossing 't's, even ones that are cited often in the short term, are far less important than articles that strike out in new directions. These are the ones that will change the direction of economics and be remembered in future history of economic thought texts.

Any literature assessment has to be based on a judgment about the future direction of economics. If one does not, one is, by default, accepting the judgment that the current approach in the profession will continue. We have a definite view of the future of economics—there will be more acceptance that the economy is complex, and that the profession, over time, will adopt certain kinds of technical mathematical, analytical and statistical tools to deal with that complexity. Models based on *a priori* assumptions will decrease, and be replaced by empirically driven models and assumptions. Behavioral economics will expand; experiments will become part of the economist's tool kit, as will complex technical tools such as cluster analysis, ultra metrics, and dimensional analysis. This increasing complexity will be accompanied by a division of labor—theorists and statisticians will be become increasingly specialized, but they will be complemented by economists who have a broad overview of where economics is going, and are trained in applying economics. Economics will stop trying to answer grand questions, such as whether the market is preferred to command and control, or if the market is efficient, and answer smaller questions such as what market structure will achieve the ends that policy makers are trying to achieve.

Since the term 'complexity' has been overused and over hyped, we want to point out that our vision is not of a grand complexity theory that pulls everything together. It is a vision that sees the economy as so complicated that simple analytical models of the aggregate economy—models that can be specified in a set of analytically solvable equations—are not likely to be helpful in understanding many of the issues that economists want to address. Thus, the Walrasian neoclassical vision of a set of solvable equations capturing the full interrelationships of the economy that can be used for planning and analysis is not going to work. Instead, we have to go into the trenches, and base our analysis on experimental and empirical data. From there we build up, using whatever analytic tools we have available. This is different from the old vision where economists mostly did the opposite—starting at the top with grand mathematical theories of a Bourbakist axiomatic sort, and then working down.

This complexity vision not only connects the various research threads that will be the future of economics, it also provides the best way to look at the economics profession itself. We see the economics profession as an evolving complex system that has competing forces operating at all times. It is a profession that can only be understood as a system in constant change and flux. Before we pursue these topics more, let us first try to define what complexity means.

3. Definitions of Complexity

Adopting a complexity vision does not require choosing among the many specific definitions of complexity.[2] But it is probably useful to note the most relevant definitions used in economics today. Three such views seem most pertinent: a general view, a dynamic view, and a computational view. The general view is the most useful for thinking about the evolution of economics as a discipline; the computational view is starting to become influential as a research methodology; and the dynamic view is relevant for both concerns. A general definition of a complex system comes from Herbert Simon (1962, p. 267):

> Roughly by a complex system I mean one made up of a large number of parts that interact in a non-simple way. In such systems, the whole is more than the sum of the parts, not in an ultimate metaphysical sense, but in the important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole. In the face of complexity, an in-principle reductionist may be at the same time a pragmatic holist.

Simon then goes on to emphasize how this definition leads to a focus on the hierarchical structure of systems. Simon emphasizes that he is drawing on older literatures, particularly general systems theory (von Bertalanffy, 1962), which he sees as including the work of economist Kenneth Boulding with cybernetics (Wiener, 1948), and information theory (Shannon & Weaver, 1948). Of these, cybernetics can be seen as a foundational form of our second variety of complexity, dynamic complexity, while information theory can be seen as a foundational form of our third variety, computational complexity.[3]

The emphasis on the problem of the whole and the parts raises two central issues in economics and for more recent approaches to complexity. One is the problem of the relationship between micro and macro in economics, which calls

---

[2]Quite famously, the MIT physicist Seth Lloyd provided (at least) 45 definitions of this concept, identifying Simon's view as one of his 45 definitions, labeled 'hierarchical' (Horgan, 1997, p. 303, n. 11).

[3]Simon saw the limits to human ability to compute as part of the foundation of bounded rationality. He saw part of this as involving the sort of logical paradoxes that concern those involved with computational complexity, and indeed his concern with these issues, led him to become one of the 'fathers of artificial intelligence' (Simon, 1969).

to mind the old problem of Keynes's 'fallacy of composition.' Walrasian approaches to macroeconomics have attempted to avoid this problem through the use of representative agent models. Others have proposed dealing with this problem through an intermediate zone between the micro and the macro, the 'meso,' which is seen as crucial to evolutionary dynamics of a complex economy (Ng, 1980; Dopfer *et al.*, 2004).[4] The second issue is the phenomenon of the apparently spontaneous 'emergence' of higher order structures out of lower order ones, an idea much emphasized by many at the Santa Fe Institute (Crutchfield, 1994), as well as by Austrian students of complexity (Lavoie, 1989), also sometimes labeled 'anagenesis' (Boulding, 1978; Rosser *et al.*, 1994).[5]

Simon's general definition also has the virtue of being close to the original meaning of the word 'complex' as found in the *Oxford English Dictionary* (1971, p. 492), where it is first defined as 'a whole, comprehending in its compass a number of parts,' from the Latin 'complectere,' meaning 'to encompass, embrace, comprehend, comprise.' Among its partial synonyms is 'complicated,' although, as Israel (2005) points out, this comes from a different Latin root, 'complicare,' meaning 'to fold together' or 'interwoven.' Israel takes the strong position that this latter is a merely epistemological concept while the former is fundamentally ontological, complaining that such figures as von Neumann (1966) mistook them as identical, although this is arguably an overly strong position.

A final virtue of this general definition is that it encompasses the current cutting-edge areas of economics—the behavioral and experimental approaches. Some who follow these approaches (Binmore and Rabin, for example, even though they disagree strongly with each other on certain issues, see Colander *et al.*, 2004a) do not consider the complexity view to be all that relevant to what they do. However, at the foundation of behavioral economics is the concept of *bounded rationality*, introduced originally by Herbert Simon. It is not just Simon, but many since who have seen complexity as implying that rationality must be bounded (Sargent, 1993; Arthur *et al.*, 1997), and thus is lying at the foundation of behavioral economics.[6]

The second definition is dynamic complexity, which is arguably the most widely used form in economics, although not on Lloyd's list of 45 definitions (Horgan, 1997, p. 303, n. 11). Rosser (1999) has codified this as 'broad tent complexity' and draws on Day (1994) for its definition. 'A dynamical system is complex if it endogenously does not tend asymptotically to a fixed point, a limit cycle, or an explosion' (Rosser, 1999, p. 170). Rosser then draws on the

[4]Further development of this form of evolutionary approach as a foundation of a complexity view of economics can be found in Potts (2000), Metcalfe & Foster (2004), and Dopfer (2005). It is worth keeping in mind that the very term 'neoclassical' was coined by Veblen, who posed the evolutionary approach as the most serious alternative to the neoclassical approach (Veblen, 1898), with Hodgson (2006) arguing that Darwinian evolution is the most fundamental of all complex systems.

[5]This approach can be seen as preceded by the British 'Emergentist' School, which arguably first emerged in Mill (1843). See also Morgan (1923).

[6]On the relation of Sargent to Simon, see Sent (1997).

criticisms of 'chaoplexity' by Horgan (1997) to argue that this broad tent view contains four successive approaches based on nonlinear dynamics:[7] cybernetics (Wiener, 1948), catastrophe theory (Thom, 1975), chaos theory (Dechert, 1996), and 'small tent' (or heterogeneous interacting agent-based) complexity.[8] This latter is identified with approaches coming initially out of Brussels (Nicolis & Prigogine, 1977), Stuttgart (Haken, 1983), and the Santa Fe Institute, with Schelling (1971) being another predecessor. This approach emphasizes dispersed and interacting heterogeneous agents (Arthur *et al.*, 1997; Hommes, 2006; Tesfatsion, 2006). For many economists this is what they mean when they refer to 'complexity models.'

Arthur *et al.* (1997, pp. 3–4) provide a summary of this approach through six characteristics: (1) dispersed interaction among heterogeneous agents;[9] (2) no global controller in the economy; (3) cross-cutting hierarchies with tangled interactions; (4) continual adaptation and learning by evolving agents; (5) perpetual novelty; and (6) out-of-equilibrium dynamics with no presumption of optimality. This approach is seen as implying bounded rationality, not rational expectations, as noted above.

Finally, we come to our third definition, that of computational complexity. While advocates of this approach emphasize its greater degree of precision, we shall also keep this to a more general level, as there are many different varieties of this concept, with arguably over half of the 45 definitions listed by Lloyd constituting one or another of its varieties. Many of these definitions are derived from the already-mentioned information theory of Shannon & Weaver (1948) (e.g., Solomonoff, 1964; Kolmogorov, 1965), which eventually boils down to descriptions of the minimum length of a computer program that will

[7]It is generally argued that dynamically complex systems must be nonlinear, although not all nonlinear systems are complex. However, Goodwin (1947) showed that coupled linear systems with lags could exhibit what are described as complex dynamics, although the normalized equivalent of such a system is nonlinear, and Turing (1952) used such systems to develop his idea of *morphogenesis*.

[8]Horgan laid out the four approaches listed here, but viewed them as a series of intellectual fads or bubbles, which were oversold and then faded, but ultimately not useful intellectually. Horgan's term of 'chaoplexity' was meant to be a mocking combination of the last two of these. Rosser (1999) countered this by arguing that they represent a cumulative development of understanding of complex economic dynamics.

[9]While it is generally argued that all this contradicts general equilibrium theory, Arrow has argued that 'One of the things that microeconomics teaches you is that individuals are not alike. There is heterogeneity, and probably the most important heterogeneity here is heterogeneity of expectations. If we didn't have heterogeneity, there would be no trade. But developing an analytic model with heterogeneous agents is difficult' (Colander *et al.*, 2004a, p. 301). This reminds us that while current macroeconomists like to describe their models as being 'Walrasian,' their frequent assumptions of representative agents with rational expectations (or minor variations on these) are far simpler than the assumptions in the Arrow–Debreu general equilibrium framework. Curiously, some of the greatest criticisms of the Arrow–Debreu general equilibrium framework have come from its own developers, as with the Sonnenschein-Mantel-Debreu Theorem (Debreu, 1974).

describe the information or system (Chaitin, 1987) or some variation of this (Rissanen, 1989).[10] A stricter view is that a system is only truly computationally complex if it is not computable at all (Blum *et al.*, 1998).[11] These authors posit non-existent computers that use the uncountable real numbers instead of the countably infinite algebraic numbers that digital computers use, with the result that usual gradations of computational complexity based on variations of the finite length of solving times collapse into each other, and only an infinite time is meaningfully complex.[12]

Advocates of this approach (Albin with Foley, 1998; Markose, 2005; Velupillai, 2000, 2005) argue that its greater precision makes it a superior vehicle for scientific research in economics. It must be admitted that there is some truth to this. Nevertheless, the vast majority of research in economics that identifies itself with complexity tends to be more of the dynamic variety described above. Furthermore, this definition is certainly less useful when we consider the question of the economics profession itself as a complex evolving system. Here we consider that the first two definitions provide a more useful construct for analysis than this admittedly challenging and substantial view of complexity, which we expect has the potential for important future research in the area of economic complexity. Not only is the economics profession a set of hierarchies, but it also evolves through a set of local interactions among dispersed networks of influence.

4. What Do We Mean by Cutting Edge Complexity Work?

These definitions are important because they give us a way to integrate the different strains of modern economics into the theme of complexity. The acceptance by the economics profession that the economy is complex signals a new openness to ideas from other disciplines, making it a more transdisciplinary field. Some types of current work falling into this more general complexity approach include the following:

- Evolutionary game theory is redefining how institutions are integrated into the analysis.
- Ecological economics is redefining how nature and the economy are viewed as interrelating in a transdisciplinary formulation.

---

[10]Velupillai (2000, 2005, 2009) discusses the relationships between these different definitions.

[11]In such cases the program is of infinite length, that is, it does not halt. A fundamental source of this may involve problems associated with the incompleteness concept of Gödel (Lewis, 1985). An application to general equilibrium is due to Richter & Wong (1999).

[12]This is linked with the much debated question of P = NP in computational complexity (Cook, 1971; Sipser, 1992), where P represents problems solvable in a time bounded above polynomially, whereas NP is bounded above exponentially or by some other higher form than polynomial. It is widely thought, but has yet to be proven definitively, that for digital computers these sets do not coincide, although they do coincide for the case of abstract real computation.

- Behavioral economics is redefining how rationality is treated.
- Econometric work dealing with the limitations of classical statistics is redefining how economists think of empirical proof.
- Complexity theory is offering a way of redefining how we conceive of general equilibrium and economic dynamics more broadly.
- Agent-based computational economic (ACE) analysis is providing an alternative to analytic modeling.
- Experimental economics is changing the way economists think about empirical work, with this being the principal method by which behavioral economics is studied.

These changes are ongoing and have, in varying degrees, entered the mainstream. As that has happened, there have been a broader set of changes in how mainstream economics sees itself. Modern economics is more willing to accept that the formal part of economics has limited applicability. It is also far more willing to question the special status of economics over the other fields of inquiry and to integrate the methods of other disciplines into their methods.[13] Thus, Becker (1976) argues for applying the economic assumption of rational economic agents to other disciplines, while others argue for bringing ideas from other disciplines into economics (Rabin, 1998).

Each of these different strains has certain characteristics that are quite different from what is presented in economic textbooks. In most textbooks today one gets the impression that economics has not changed much during the last 50 years. Essentially, one learns a paradigm that develops a simple analytic–deductive model, sometimes called the Max-U model. The microeconomics taught in these texts is some variation on the Max-U model presented with little contextual flavor that characterized Marshall's use of it. The Max-U model presented in the standard text focuses almost entirely on efficiency and optimization, assuming agents are rational, selfish, and are operating in an environment that arrives at a unique equilibrium.

The Max-U model has been explored to death and, from a cutting-edge view, is no longer of much interest. (That doesn't mean it doesn't still have considerable relevance. There are still many practical applications that warrant research; however, from a cutting edge standpoint, we've pulled about all we can from it.) That is why a major part of the new cutting-edge work moves beyond these assumptions. While it does not deny the usefulness or insight provided by that model, it does not see a model based only on these assumptions as sufficient, and is therefore pushing the envelope on each of those assumptions. Some examples of how cutting-edge work is questioning these neoclassical assumptions would be the following:

- Cutting-edge economics researchers are expanding the meaning of rationality to include a much broader range of agent actions that reflect actual actions; in the

[13] As Colander (1995) argues, the approach we are describing is consistent with a Marshallian methodology, but inconsistent with a Walrasian methodology. See also Loasby (1989).

new approach, individuals are purposeful (incentives still matter) but are not necessarily formally rational. The new research considers the behavioral foundations of actions, using experiments to determine what people actually do, rather than simply basing their arguments on what people rationally should do.[14] The work in game theory (by economists such as Young, 1998) is pushing rationality to its limits to demonstrate the importance of the expectations and the information environment in people's decisions. The cutting-edge work that is being done here is going beyond the traditional definition of rationality, with extended versions of Herbert Simon's bounded rationality increasingly being accepted.

- Cutting-edge researchers are moving away from a narrow view of selfishness. While textbook economics generally assumes that agents only care about themselves, the new work is trying to come to grips with a more realistic sense of individuals who, while they are self-interested, are also social beings, concerned about others and deriving happiness from interacting with others (Fehr & Schmidt, 1999).
- Cutting-edge researchers are moving away from the assumption of a unique equilibrium, and are dealing with complicated systems that have multiple equilibria, path dependency, and no clear-cut answer. A complex economy does not have a single equilibrium; it has many basins of attraction. The question researchers ask is which basin is sustainable. In this work, aggregate equilibrium is not assumed to be a state in which all components of the economy are in equilibrium; instead it is assumed to be a state in which the components may be continually in flux, even as the aggregate economy is in equilibrium (Delli Gatti *et al.*, 2008).

Combined, these changes can be summarized as a movement from an economics of rationality, selfishness, and equilibrium, to an economics of purposeful behavior, enlightened self-interest, and sustainability. Cutting-edge work helps to move that transformation along.

5. Changes in Research Methods

Another aspect of cutting-edge work that is consistent with the complexity era involves changes in research methods that can serve as a catalyst for many changes in the profession. For example, advances in computing technology have led to new approaches such as agent-based modeling. This allows economists to analyze complicated systems, with more complicated interactions between the agents, out of which higher-order structures may emerge or self-organize. In addition, instead of assuming optimal behavior, economists are using lab, field and natural experiments to determine what people actually do. As economists have started to use these new techniques they are taking notice of institutions,

[14]This work is beginning to integrate work in psychology such as John Payne *et al.* (1993), which has used experimental methods to analyze choice and to see how people actually make decisions, rather than just assume rationality.

since the incentives embodied in those institutions are often central in understanding people's behavior, as in the studies by Ostrom (1990) and others of how different institutional arrangements can lead to very different outcomes in the management of common property.

This change is being accompanied by a change in the deductive nature of economic reasoning. The new work is based more on empirical inductive reasoning, and far less on pure deductive reasoning. As this is happening, the math being used in economic analysis is becoming less the Bourbakian math of 'theorem-proof,' and more applied mathematics, which is designed to come up with answers about policy issues, and not just talk about general issues (Weintraub, 2002). Set theory and calculus, which come to definite results, are being replaced by game theory, which seldom comes to a definite conclusion independent of the precise structure of the game. For example, current work on auctions combines insights from game theory with experimental results, which are then used in practice (Banks *et al.*, 2003).

6. The Lack of Impact of Cutting-edge Work on Modern Macroeconomics

Changes in micro theory have not occurred in macroeconomics. In fact, the evolution of macroeconomic thinking in the United States has gone the other way. There has been a movement away from a rough and ready macro theory (which characterized the macroeconomics of the 1960s) and towards an analytic macro theory based on abstract, representative agent models that rely heavily on the assumptions of equilibrium. This macro work goes under the name new Classical, Real Business cycle, and the Dynamic Stochastic General Equilibrium (DSGE) theory, and has become the mainstream in the US.

In part, this development is understandable. The macro theory of the 1960s claimed a much stronger theoretical foundation than was warranted, and many of its conclusions were not supported by empirical evidence or theory. However, while the new theoretical models have done a good job of eliminating the old theory, it is less clear what this work has added to our understanding of the macroeconomy. At best, the results of the new macro models can be roughly calibrated with the empirical evidence, but often these new models do no better than any other model, and the only claim they have to being preferred is aesthetic—they have micro foundations. However, it is a strange micro foundation—a micro foundation based on assumptions of no heterogeneous agent interaction, when, for many people, it is precisely the heterogeneous agent interaction that leads to central characteristics of the macro economy.[15] This is the essential insight of Keynes' fallacy of composition (Holt, 2011).

---

[15]There have been some DSGE models that allow for heterogeneous agents (Krusell & Smith, 1998), but these models do not involve any direct interactions between the agents, with the heterogeneity involving an assumed infinite continuum over some interval that essentially operates together as if it is a representative agent, albeit with some minor variations in outcomes, but not driven by agent interactions.

In our view, the interesting cutting-edge work in macro is not in the theoretical developments organized around representative agent micro foundations, but the work that views the macroeconomy as a complex system. In this work, one sees the macroeconomy as being endogenously organized. The issue is not why there are fluctuations in the macro economy, but why is there so little instability where complex interactions could generate chaos.[16] The belief that one could develop a micro foundation for macroeconomics without considering the feedback of the macro system on the individual is beyond belief. While it may still make sense to push analytic macro theory as far as one can, to see whether it will provide any insights, such analytic extensions of pure theoretical models based on assumptions that are far from reality offer little hope for policy guidance. In the absence of a pure theoretical foundation, macro policy is best based on statistical models that pull as much information as possible from the data. Empirical macro precedes theoretical macro.

7. Conclusion

When we first made the above arguments about complexity nearly a decade ago, they were far more controversial than they are now. Since then, economics has become more open to the approaches we suggested constitute complexity economics; as a result, complexity economics is becoming just economics. We are not saying that the movement to the complexity era is going to be smooth, or that the work is without problems. Some areas, such as experimental economics, have become fads, and an ever-increasing number of economists are including experimental work in their research. Such areas will require a weeding out, as researchers arrive at consensus about what is and isn't an acceptable experiment (Binmore & Shaked, 2010; Fehr & Schmidt, 2010).

Other work, such as ACE modeling still has problems getting published because it doesn't fit well into a journal format, and it is difficult to figure out what we can learn from these models. Similar problems exist for the craftsman approach to econometrics discussed in Colander (2009), in which the econometrician interacts with the data and makes judgments while doing the analysis rather than working as a technician who is applying specific methods to data analysis. How does one judge the judgment? These issues will be debated over the next decade, and tentative answers will be arrived at. Once they are, the true cutting-edge economists will no longer be involved; they will have moved on to other problems. And this is the way it should be in an ever-changing, dynamic and evolving profession.

[16]Of course, while true mathematical chaos is locally unstable, its fluctuations remain bounded, thus being consistent with the 'corridor of stability' argument of Leijonhufvud (1973, 2009), along with the deep ecology idea of Holling (1973) of a possible tradeoff between resilience and stability.

References

Albin, P.S. with Foley, D.K. (1998) *Barriers and Bounds to Rationality: Essay in Economic Complexity in Interactive Systems* (Princeton: Princeton University Press).

Arthur, W.B., Durlauf, S.N. & Lane, D.A. (1997) Introduction, in: W.B. Arthur, S.N. Durlauf & D.A. Lane (Eds) *The Economy as an Evolving Complex System II* (Redwood City: Addison-Wesley).

Banks, J., Olson, M., Porter, D., Rassenti, S. & Smith, V. (2003) Theory, experiment, and the Federal Communications Commission spectrum auctions, *Journal of Economic Behavior and Organization*, 51, pp. 303–350.

Becker, G.S. (1976) *The Economic Approach to Human Behavior* (Chicago: University of Chicago Press).

Binmore, K. & Shaked, A. (2010) Experimental economics: where next?, *Journal of Economic Behavior and Organization*, 73(1), pp. 87–100.

Blum, L., Cucker, F., Shub, M. & Smale, S. (1998) *Complexity and Real Computation* (New York: Springer-Verlag).

Boulding, K. (1978) *Ecodynamics: A New Theory of Societal Evolution* (Beverly Hills, CA: Sage).

Chaitin, G.J. (1987) *Algorithmic Information Theory* (Cambridge: Cambridge University Press).

Colander, D. (1995) Marshallian general equilibrium analysis, *Eastern Economic Journal*, 21, pp. 281–293.

Colander, D. (2009) Economists, incentives, and empirical work, *EconomicEjournal.* Available at: http://www.economics-ejournal.org/economics/journalarticles/2009-9

Colander, D., Holt, R.P.F. & Rosser, J.B., Jr. (2004a) *The Changing Face of Economics: Conversations with Cutting Edge Economists* (Ann Arbor: University of Michigan Press).

Colander, D., Holt, R.P.F. & Rosser, J.B., Jr. (2004b) The changing face of mainstream economics, *Review of Political Economy*, 16(4), pp. 485–499.

Cook, S.A. (1971) The complexity of theorem proving procedures, *Proceedings of the Third ACM Symposium on Theory of Computing*, pp. 151–158.

Crutchfield, J. (1994) The calculi of emergence: computation, dynamics and induction, *Physica D*, 75, pp. 11–54.

Day, R.H. (1994) *Complex Economic Dynamics, Volume I: An Introduction to Dynamical Systems and Market Mechanisms* (Cambridge: MIT Press).

Debreu, G. (1974) Excess demand functions, *Journal of Mathematical Economics*, 1, pp. 15–21.

Dechert, W.D. (Ed.) (1996) *Chaos Theory in Economics: Methods, Models and Evidence* (Aldershot, UK: Edward Elgar).

Delli Gatti, D., Gafeo, E., Gallegati, M., Giulioni, G. & Palestrini, A. (2008) *Emergent Macroeconomics: An Agent-Based Approach to Business Fluctuations* (Milan: Springer).

Dopfer, K. (Ed.) (2005) *The Evolutionary Foundations of Economics* (Cambridge: Cambridge University Press).

Dopfer, K., Foster, J. & Potts, J. (2004) Micro-meso-macro, *Journal of Evolutionary Economics*, 14, pp. 263–279.

Fehr, E. & Schmidt, K.M. (1999) A theory of fairness, competition and cooperation, *Quarterly Journal of Economics*, 114, pp. 817–868.

Fehr, E. & Schmidt, K.M. (2010) On inequity aversion: a reply to Binmore and Shaked, *Journal of Economic Behavior and Organization*, 73(1), pp. 101–108.

Goodwin, R.M. (1947) Dynamic coupling with especial reference to markets having production lags, *Econometrica*, 15, pp. 181–204.

Haken, H. (1983) *Synergetics: Non-Equilibrium Phase Transitions and Social Measurement*, 3rd edn (Berlin: Springer-Verlag).

Hodgson, G.M. (2006) *Economics in the Shadows of Darwin and Marx* (Cheltenham, UK: Edward Elgar).

Holling, C.S. (1973) Resilience and stability of ecological systems, *Annual Review of Ecology and Systematics*, 4, pp. 1–24.

Holt, R.P.F. (2011) The Post-Keynesian critique of the mainstream theory and approaches to economic policy, in: G. Harcourt & P. Kriesler (Eds) *The Handbook of Post-Keynesian Economics* (Oxford: Oxford University Press).

Hommes, C.H. (2006) Heterogeneous agent models in economics and finance, in: K.L. Judd & L. Tesfatsion (Eds) *Handbook of Computational Economics: Agent-Based Computational Economics, Vol. 2* (Amsterdam: North-Holland).
Horgan, J. (1997) *The End of Science: Facing the Limits of Knowledge in the Twilight of the Scientific Age* (New York: Basic Books).
Israel, G. (2005) The science of complexity: epistemological problems and perspectives, *Science in Context*, 11, pp. 1–31.
Kolmogorov, A.N. (1965) Three approaches to quantitative definition of information, *Problems of Information Transmission*, 1, pp. 4–7.
Krusell, P. & Smith, A.A. (1998) Income and wealth heterogeneity in the macroeconomy, *Journal of Political Economy*, 106(5), pp. 867–896.
Lavoie, D. (1989) Economic chaos or spontaneous order? Implications for political economy of the new view of science, *Cato Journal*, 8, pp. 613–635.
Leijonhufvud, A. (1973) Effective demand failures, *Swedish Journal of Economics*, 75, pp. 27–48.
Leijonhufvud, A. (2009) Out of the corridor: Keynes and the crisis, *Cambridge Journal of Economics*, 33, pp. 741–757.
Lewis, A.A. (1985) On effectively computable realizations of choice functions, *Mathematical Social Sciences*, 10, pp. 43–80.
Loasby, B. (1989) *The Mind and Method of the Economist: A Critical Appraisal of Major Economists in the Twentieth Century* (Cheltenham, UK: Edward Elgar).
Markose, S.M. (2005) Computability and evolutionary complexity: markets as complex adaptive systems (CAS), *Economic Journal*, 115, pp. F159–F192.
Metcalfe, J.S. & Foster, J. (Eds) (2004) *Evolution and Economic Complexity* (Cheltenham, UK: Edward Elgar).
Mill, J.S. (1843) *Ratiocinative and Inductive Logic* (London: Longmans Green).
Morgan, C.L. (1923) *Emergent Evolution* (London: Williams and Norgate).
Ng, Y.K. (1980) Macroeconomics with non-perfect competition, *Economic Journal*, 90, pp. 598–610.
Nicolis, G. & Prigogine, I (1977) *Self-Organization in Nonequilibrium Systems: From Dissipative Structures to Order through Fluctuations* (New York: Wiley-Interscience).
Ostrom, E. (1990) *Governing the Commons* (Cambridge: Cambridge University Press).
Oxford English Dictionary (1971) *The Compact Edition of the Oxford English Dictionary, Volume A-O* (Oxford: Oxford University Press).
Payne, J., Bettman, J. & Johnson, E. (1993) *The Adaptive Decision Maker* (New York: Cambridge University Press).
Potts, J. (2000) *The New Evolutionary Microeconomics: Complexity, Competence and Adaptive Behavior* (Cheltenham, UK: Edward Elgar).
Rabin, M. (1998) Psychology and economics, *Journal of Economic Literature*, 36, pp. 11–46.
Richter, M.K. & Wong, K.C. (1999) Non-computability of competitive equilibrium, *Economic Theory*, 14, pp. 1–28.
Rissanen, J. (1989) *Stochastic Complexity in Statistical Inquiry* (Singapore: World Scientific).
Rosser, J.B., Jr., (1999) On the complexities of complex economic dynamics, *Journal of Economic Perspectives*, 13(4), pp. 169–192.
Rosser, J.B., Jr., Folke, C., Folke, G., Isomäki, H., Perrings, C. & Puu, T. (1994) Discontinuous change in multilevel hierarchical systems, *Systems Research*, 11(3), pp. 77–93.
Rosser, J.B., Jr., Holt, R.P.F. & Colander, D. (2010) *European Economics at a Crossroads* (Cheltenham, UK: Edward Elgar).
Samuelson, P.A. (1937) A note on measurement of utility, *Review of Economic Studies*, 4, pp. 155–161.
Sargent, T.J. (1993) *Bounded Rationality in Macroeconomics* (Oxford: Clarendon Press).
Schelling, T.C. (1971) Dynamic models of segregation, *Journal of Mathematical Sociology*, 1, pp. 143–186.
Sent, E.-M. (1997) Sargent versus Simon: bounded rationality unbound, *Cambridge Journal of Economics*, 21, pp. 323–338.
Shannon, C. & Weaver, W. (1948) *The Mathematical Theory of Communication* (Urbana: University of Illinois Press).

Simon, H.A. (1962) The architecture of complexity, *Proceedings of the American Philosophical Society*, 106, pp. 467–482.

Simon, H.A. (1969) *The Sciences of the Artificial* (Cambridge: MIT Press).

Sipser, M. (1992) The history and status of the P versus NP question, *Proceedings of the 24th ACM Symposium on Theory of Computing*, pp. 603–618.

Solomonoff, R.J. (1964) A formal theory of inductive inference parts I and II, *Information and Control*, 7, pp. 1–22, 224–254.

Tesfatsion, L.S. (2006) Agent-based computational economics: a constructive approach to economic theory, in: K.L. Judd & L. Tesfatsion (Eds) *Handbook of Computational Economics: Agent-Based Computational Economics, Vol. 2* (Amsterdam: Elsevier).

Thom, R. (1975) *Structural Stability and Morphogenesis: An Outline of a Theory of Models* (New York: Benjamin).

Turing, A.M. (1952) The chemical basis of morphogenesis, *Philosophical Transactions of the Royal Society*, 237, pp. 37–72.

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

Velupillai, K.V. (2000) *Computable Economics* (Oxford: Oxford University Press).

Velupillai, K.V. (2005) A primer on the tools and concepts of computable economics, in: K.V. Velupillai (Ed.) *Computability, Complexity and Constructivity in Economic Analysis* (Victoria: Blackwell).

Velupillai, K.V. (2009) A computable economist's perspectives on computational complexity, in: J.B. Rosser, Jr. (Ed.) *Handbook of Complexity Research* (Cheltenham, UK: Edward Elgar).

Von Bertalanffy, L. (1962) *General Systems Theory* (New York: George Braziller).

Von Neumann, J. (1966) *Theory of Self-Reproducing Automata* (Urbana: University of Illinois Press).

Weintraub, E.R. (2002) *How Economics Became a Mathematical Science* (Durham, NC: Duke University Press).

Wiener, N. (1948) *Cybernetics, or Control and Communication in the Animal and the Machine* (New York: Wiley).

Young, H.P. (1998) *Individual Strategy and Social Structure: An Evolutionary Theory of Institutions* (Princeton: Princeton University Press).