Guest Editorial: Agent-Based Modelling of Evolutionary Economic Systems

I. Overview

A modern market-based economy is an example of a complex adaptive system, consisting of a decentralized collection of autonomous agents interacting in various market contexts. These massively parallel local interactions give rise to global regularities such as trade networks, socially accepted monies, market protocols, business cycles and the common adoption of technological innovations. The recent advent of powerful new computational tools, in particular the development of new techniques in evolutionary computation, is giving economists an increased opportunity to study market-based economies in their true complex form.

The primary objective of this special issue is to introduce, motivate, and explore through concrete applications the potential usefulness of *agent-based computational economics* (*ACE*), a new methodology for the study of economies as complex adaptive systems. Specifically, ACE is the computational study of economies modelled as evolving systems of autonomous interacting agents.[1]

One principal concern of ACE researchers is to understand why certain global regularities have been observed to evolve and persist in decentralized market economies despite the absence of top-down planning and control. The challenge is to demonstrate *constructively* how these global regularities might arise from the bottom up, through the repeated local interactions of autonomous agents.

A second principal concern of ACE researchers is to use ACE frameworks normatively, as computational laboratories within which alternative socioeconomic structures can be studied and tested with regard to their effects on individual behavior, interaction networks, and social welfare. This normative concern complements a descriptive concern with actually observed global regularities by seeking deeper possible explanations not only for why certain global regularities have been observed to evolve but also why others have not.

ACE researchers thus blend elements from evolutionary economics, cognitive science, and computer science in an attempt to understand the bottom-up emergence of global regularities. This effort raises numerous challenging issues.

For example, the modelling of interactions among economic agents is a major issue for ACE researchers. Will traditional game theory tools suffice, or will these tools have to be substantially modified or even replaced? Does the growing interest in "network games" represent a new departure or old wine in new bottles? Under what conditions will coordination tend to emerge, in terms both of the persistence of interaction networks and the persistence of the expressed behaviors supported by these networks? And in what sense (if any) can this coordination be said to be optimal?[2]

The representation of learning in dynamic strategic multi-agent contexts is another critical issue for ACE researchers. What tools can be used to measure the degree to which economic agents co-adapt for any given set of behavioral rules, and the manner in which they co-evolve as they change their behavioral rules over time? What measures can be applied to determine the extent to which outcomes are the result of learning per se rather than the direct consequence of the basic "rules of the game" in the form of institutionalized structures and protocols?

Yet another critical issue is the relationship between individuals and social groupings. How do individual behaviors affect group formation, and how does the existence of social groupings in turn affect the emergence of individual behaviors? Can this intricate two-way feedback process be modelled in a compelling way?

Finally, ACE researchers need to construct computational laboratories that permit the rigorous study of economic processes through controlled experimentation. How can the resulting experimental findings be effectively communicated to other researchers by means of descriptive statistics and graphical visualizations without information overload? And how can these findings be validated by comparisons with data obtained from other sources, such as human-subject experimental data, panel data, and field study data?

As will now be outlined in summary form, the articles included in this special issue address these questions in a variety of specific problem contexts.

II. Article Synopses

The nine contributions comprising this special issue apply the ACE methodology to a diverse range of economic topics. The first six contributions focus on specific types of markets: stock markets, foreign exchange markets, oligopolies; labor markets, and electricity markets. The seventh contribution considers a multi-market selection process. The eighth contribution considers the ability to achieve goals at the macroeconomic level without direct control of self-interested economic agents at the microeconomic level. The ninth and final contribution motivates and illustrates the construction of a computational laboratory for the study of evolutionary trade networks.

[1] The ACE Web site [1] provides extensive resources related to this methodology, including surveys, an annotated syllabus of readings, software, teaching materials, information on conferences and special journal issues, and pointers to individual researchers and research groups.

[2] For pointers to resources focusing on the evolution of interaction networks, including network games, visit the Formation of Economic and Social Networks Web Site [2].

Conventional models of securities markets based on assumptions of rational choice and the efficient markets hypothesis are extremely elegant in form. Unfortunately, no single model to date has proved capable of explaining the basic empirical features of real financial markets, including the pattern of relative returns, trading volumes, the amount and persistence of volatility, and cross correlations among returns, volume, and volatility.

The first contribution, by Blake LeBaron [3], calibrates an agent-based computational stock market model to aggregate macroeconomic and financial data. Agents co-evolve their trading rules based on differing amounts of past data, with fitnesses measured by wealth levels. LeBaron calibrates this model to the growth and variability of dividend payments in the United States. He is able to show that the calibrated model generates return, volume, and volatility features remarkably similar to those characterizing actual financial time series data.

Foreign exchange markets have also proved to be extremely difficult to model with any predictive power using conventional modelling approaches. The authors of the second contribution, Kiyoshi Izumi and Kazuhiro Ueda [4], propose a new agent-based approach to the modelling of foreign exchange markets.

Specifically, Izumi and Ueda use field data (dealer interviews and questionnaires) to construct behavioral rules governing agent interactions and learning in a multi-agent foreign exchange model. The agents in their model compete with each other to develop methods for predicting changes in future exchange rates, with fitness measured by profitability. The objective of the authors is to provide a quantitative microfoundations explanation for empirically observed macro regularities in foreign exchange markets. They are able to show that their model provides a possible explanation for the emergence of the following three empirical features: peaked and fat-tailed rate change distributions; a negative correlation between trading volume and exchange rate volatility, and a "contrary opinions" phenomenon in which convergence of opinion causes a predicted event to fail to materialize.

Previous studies in evolutionary economics have examined the effects of particular types of individual behavioral rules on market development, price dynamics, industry structure, and growth. In contrast, organizational theory studies have tended to stress the effect of a firm's organizational structure on its resulting behavior, but without explicit attention paid to interactions with other firms in the market. The authors of the third contribution, Herbert Dawid, Marc Reimann, and Bernd Bullnheimer [5], use a stylized agent-based model of an industry to explore how both industry structure and individual firm properties affect the form of the optimal behavioral rule for a participant firm.

More precisely, Dawid et al. consider a collection of firms participating in the production of closely related goods (e.g., the soft drink industry). In each successive time period, each firm must choose whether to produce an already existing product variety or to introduce a new product variant. The demand for each product variety dies after a stochastically determined amount of time, and this obsolescence implies that each firm must engage in some degree of innovation in order to sustain its profitability. Firms differ in their ability to imitate existing product designs and in their ability to design new product variants due to random effects and to "learning by doing" effects. Each firm has an innovation rule determining its choice to innovate or not, and the firms co-evolve these rules over time on the basis of anticipated profitability. The authors use systematic computational experiments to explore how, for optimal profitability, the innovation rule of a firm should adapt both to the structural properties of the industry as a whole and to the structural properties of the individual firms which comprise it.

The fourth contribution, by Troy Tassier and Filippo Menczer [6], focuses on an interesting puzzle regarding the prominent role of job referral networks in U.S. labor markets. The authors note that a robust finding for U.S. labor markets is that approximately 50 percent of workers at any given time have obtained their jobs through referral-based hiring. In order for referral-based hiring to be this effective, the referral networks must be efficiently transferring job information between employers and potential workers. On the other hand, most job referrals in the U.S. labor market come from friends, relatives, or other social contacts, not from contacts chosen specifically for job referral. Why, then, do these socially determined networks also perform so well as referral networks?

Tassier and Menczer construct an agent-based computational model in which potential workers engage in both social network formation and direct job search. They then study the properties of the social networks that evolve in order to establish the extent to which these networks transfer job information efficiently. Their model yields two main results. First, the evolved social networks have "small-world network" properties, in the sense that they are both very clustered (locally structured) and yet have global reach, and these two properties enhance the ability of the social networks to perform as job referral networks. Second, as evolution progresses, agents nevertheless ultimately expend more energy on network formation and/or direct job search than is socially efficient.

In past years, electricity in many industrialized countries has been supplied by monopolistic utilities operating under the regulatory control of various government agencies. Support for this regulated form has recently been eroding, however, due to a growing perception that it has failed to provide proper incentives for efficient market operation. In consequence, serious efforts are now being made by many countries to restructure their electric power industries into more competitive forms with much greater leeway given to private market incentives. Unfortunately, the complexity of the electric power industry makes it extremely difficult to predict in advance the consequences of these restructuring efforts using standard statistical and analytical tools.

The authors of the fifth contribution, Derek Bunn and Fernando Oliveira [7], construct an agent-based computational model of a wholesale electricity market to explore the possible effects of the New Electricity Trading Arrangements (NETA) introduced in the United Kingdom in March 2001. Their model incorporates the following critical features of the NETA market design: strategically interacting market participants (electricity generators and energy purchasers for end-use customers); a system operator; interactions between two different markets (a bilateral market and a balancing mechanism) and a settlement process; determination of day-ahead mark-ups on previous-day price offers by means of reinforcement learning; and daily dynamic constraints. The authors apply this NETA computational model to the full electricity system of England and Wales as it existed in summer 2000. They then use their experimental findings to provide insights about possible market equilibria under NETA as a function of both market structure and agent characteristics.

In the sixth contribution, authors James Nicolaisen, Valentin Petrov, and Leigh Tesfatsion [8] also construct an agent-based computational model of a restructured wholesale electricity market with strategically interacting sellers (generators) and buyers (energy purchasers for end-use customers). Prices are determined by means of a discriminatory double auction run by a clearinghouse (system operator). In each successive auction round, the sellers and buyers determine their price offers by means of reinforcement learning. The authors investigate three different specifications for the reinforcement learning parameters. For each learning specification, they conduct a systematic computational study of the effects of differing capacity and concentration conditions on market power and market efficiency. They show that high market efficiency is generally attained, and that market microstructure is strongly predictive for the relative market power of sellers and buyers, independently of the values set for the reinforcement learning parameters.

The authors of the seventh contribution, Hisao Ishibuchi, Ryoji Sakamoto, and Tomoharu Nakashima [9], explore the evolution of game strategies in a simple but interesting coordination game in which spatially located agents compete for market advantage. The interest of the authors is to determine whether an optimal coordination pattern will emerge despite the absence of any top-down coordination mechanism.

The authors consider a collection of agents situated in a two-dimensional world who have different transaction costs with respect to m markets located within this world. At the beginning of each round, each agent selects one of the markets in which to sell its products without knowledge of the market selections being made simultaneously by all other agents. The coordination difficulty is that the price in each market is a decreasing function of the total product supplied in that market, implying that (all else equal) the profit of an agent participating in a market is a decreasing function of the number of agents participating in that market. At the end of each selection round, each agent updates its current strategy (market selection) by selecting a new strategy from among its neighbors' strategies with selection probabilities proportional to fitness (profitability). The strategy of each agent also has a chance of being replaced with another randomly-selected strategy in accordance with a fixed mutation probability. The authors run extensive computational experiments for an illustrative case of their market selection game with 100 agents and 5 markets. They find for this case that the agents obtain almost the same average payoff as they would receive if market selections were instead determined by means of a top-down global maximization of total agent payoffs.

In the eighth contribution, authors Keiki Takadama, Takao Terano, and Katsunori Shimohara [10] begin by posing an age-old economic question: How can administrators provide effective oversight for a complex economic system in which many economic agents interact with each other in accordance with their own self-interests? The main objective of their paper is to provide constructive support for the following claim: Administrators should make use of properties arising from interactions among economic agents instead of controlling agents directly.

The authors develop an agent-based model of an organization consisting of an administrative party and economic agents. The administrative party has four possible levels of intervention for controlling the economic agents, ranging from Level 0 (no intervention) to Level 4 (close behavioral supervision and evaluation). The economic agents have their own goals, and they use a form of classifier system to adapt their behaviors on the basis of local information obtained from agent-agent and agent-environment interactions. The authors apply this organizational model to a specific city development problem in which the administrative party is a government whose objective is to achieve a compact city size and the economic agents are companies competing for good locations within the city. Experimental results for this application indicate that the most cost-effective level of intervention for government is Level 1 (evaluation intervention), in which the companies behave to maximize local benefits but their behaviors are evaluated in terms of the government's global objective. Nevertheless, this intervention does not actually result in a smaller city size relative to Level 0 because it decreases the incentives of the companies to engage in solution exploration.

A current drawback of ACE modelling for many economists is the perceived need for strong programming skills. A *computational laboratory* (*CL*) is a framework for controlled computational experimentation that permits researchers to engage in serious computational research even if they have only modest programming skills. A CL can present a clear and easily manipulated graphical-user interface that allows an inexperienced user to test systematically the sensitivity of a system to changes in a wide variety of key parameters without the need to do any original programming. On the other hand, a CL can be designed to be both modular and extensible. Thus, as users gain more experience and confidence, they can begin to experiment with alternative module implementations to broaden the range of system applications encompassed by the CL.

The final article in this special issue, by David Mc-

Fadzean, Deron Stewart, and Leigh Tesfatsion [11], develops a CL designed specifically for the study of trade network formation in a variety of market contexts. This CL, referred to as the *Trade Network Game* (*TNG*) *Lab*, comprises buyers, sellers, and dealers who repeatedly search for preferred trade partners, engage in risky trades modelled as noncooperative games, and evolve their trade strategies over time. The basic objective of the authors is to explain the architecture of the TNG Lab and to demonstrate its capabilities and usefulness by means of illustrative experiments. Another objective, however, is to use the example of the TNG Lab to encourage the routine construction and use of CLs for social science applications.

III. Suggested Additional Readings

Readers of the *IEEE Transactions on Evolutionary Computation* are no doubt already well acquainted with the general literature on complex adaptive systems. Here we suggest a few introductory readings related to the ACE study of economies as complex adaptive systems that might not be so well known to this readership and that would serve as useful background readings to the more specialized ACE studies included in this issue.[3] The readings are taken up roughly in the order of their publication.

Schelling [12] is a classic work on the collective consequences of individual behavior. Working with familiar examples from everyday life, and without the aid of sophisticated computational tools, Schelling makes the case that behavior in the aggregate can be far more than the simple summation of individual behaviors. The well-known monograph by Epstein and Axtell [13] was directly inspired by Schelling's work. Epstein and Axtell use relatively simple experiments to demonstrate the potential usefulness of agent-based computational modelling for social science applications.

Skyrms [14] investigates traditional problems of social contracting without the traditional presumption of rational decision-makers. Making use of ideas from evolutionary game theory, in a non-technical manner, he offers new interpretations for a variety of social phenomena such as mutual aid, commitment, and social conventions. Axelrod [15] provides an interesting sequel to his classic study [16] on the evolution of cooperation among agents playing iterated prisoner's dilemma games. He collects together seven of his subsequent essays on the evolution of cooperation that go beyond the basic prisoner's dilemma paradigm, adds new prefaces to each, and sets all in context in an extensive introductory chapter.

The contributors to the volume edited by Prietula et al. [17] stress the computational modelling of organizations as multi-agent systems, inspired by the early work of Herbert Simon in the 1950s. Object-oriented methodology underlies many of the contributions. Gilbert and Troitzsch [18] have written a practical guide to the use of computational methods in the social sciences, stressing applications where complex behaviors emerge from relatively simple activities. They describe a variety of computational models and tools at a level of detail that should permit even readers with limited programming experience to design and carry out their own computational studies.

Gintis [19] takes a strongly problem-oriented approach to agent-based evolutionary modelling, with a stress on low-rationality game dynamics. He emphasizes the need for better models of individual agents in view of the numerous anomalies discovered in laboratory experiments between actual human-subject behaviors and the behaviors predicted by traditional rational-agent theories.

All of the works cited above are relatively non-technical. For more specialized technical studies focusing on the modelling of economies as evolving complex systems, readers can turn to the Santa Fe Institute proceedings volume edited by Arthur et al. [20]. The well-known Santa Fe artificial stock market developed by W. Brian Arthur, John Holland, Blake LeBaron, Richard Palmer, and Paul Tayler is presented in the first contribution. Other contributions making direct use of agent-based computational modelling to study electoral competition, communication networks, and trade network formation are grouped together at the end of the volume.

Finally, readers of the special issue at hand might be interested in two other ACE special journal issues that have recently appeared. Contributors to the ACE special issue guest edited by Tesfatsion [21] for the *Journal of Economic Dynamics and Control* use agent-based computational laboratories to explore efficiency and welfare concerns in a variety of market contexts: financial markets, labor markets, retail fish markets, business-to-business markets, electricity markets, entertainment markets, automated e-commerce markets, and cattle pasture access markets in North Cameroon. Contributors to the ACE special issue guest-edited by Tesfatsion [22] for *Computational Economics* use stylized problem contexts to explore general economic concerns such as the evolution of norms, self-organization, and agent learning.

Acknowledgments

The guest editor is grateful to the IEEE-TEC Editor-in-Chief, David Fogel, and to all of the contributing authors and anonymous referees for helping to bring this special issue project to a successful conclusion.

References

[1] Leigh Tesfatsion, Agent-Based Computational Economics Web Site, Department of Economics, Iowa State University, accessible at http://www.econ.iastate.edu/tesfatsi/ace.htm
[2] Leigh Tesfatsion, Formation of Economic and Social Networks Web Site, Department of Economics, Iowa State University, accessible at http://www.econ.iastate.edu/tesfatsi/netgroup.htm
[3] Blake LeBaron, "Empirical Regularities from Interacting Long and Short Horizon Investors in an Agent-Based Stock Market" *IEEE Transactions on Evolutionary Computation*, this issue.
[4] Kiyoshi Izumi and Kazuhiro Ueda, "Phase Transition in a Foreign Exchange Market: Analysis Based on an Artificial Market Approach," *IEEE Transactions on Evolutionary Computation*, this issue.
[5] Herbert Dawid, Marc Reimann, and Bernd Bullnheimer, "To Innovate or Not to Innovate?," *IEEE Transactions on Evolutionary Computation*, this issue.

[3] A much more extensive collection of readings, with accompanying annotations, can be browsed at the ACE Web site [1].

[6] Troy Tassier and Filippo Menczer, "Emerging Small-World Referral Networks in Evolutionary Labor Markets," *IEEE Transactions on Evolutionary Computation*, this issue.
[7] Derek W. Bunn and Fernando S. Oliveira, "Agent-Based Simulation: An Application to the New Electricity Trading Arrangements of England and Wales," *IEEE Transactions on Evolutionary Computation*, this issue.
[8] James Nicolaisen, Valentin Petrov, and Leigh Tesfatsion, "Market Power and Efficiency in a Computational Electricity Market with Discriminatory Double-Auction Pricing," *IEEE Transactions on Evolutionary Computation*, this issue.
[9] Hisao Ishibuchi, Ryoji Sakamoto, and Tomoharu Nakashima, "Evolution of Unplanned Coordination in a Market Selection Game," *IEEE Transactions on Evolutionary Computation*, this issue.
[10] Keiki Takadama, Takao Terano, and Katsunori Shimohara, "Non-Governance Rather than Governance in a Multiagent Economic Society," *IEEE Transactions on Evolutionary Computation*, this issue.
[11] David McFadzean, Deron Stewart, and Leigh Tesfatsion, "A Computational Laboratory for Evolutionary Trade Networks," *IEEE Transactions on Evolutionary Computation*, this issue.
[12] Thomas C. Schelling, *Micromotives and Macro Behavior*, New York, NY: W. W. Norton & Company, 1978.
[13] Joshua M. Epstein and Robert Axtell, *Growing Artificial Societies: Social Science from the Bottom Up*, Cambridge, MA: The MIT Press, 1996.
[14] Brian Skyrms, *Evolution of the Social Contract*, Cambridge, UK: The Cambridge University Press, 1996.
[15] Robert Axelrod, *The Complexity of Cooperation: Agent-Based Models of Conflict and Cooperation*, Princeton, NJ: The Princeton University Press, 1997.
[16] Robert Axelrod, *The Evolution of Cooperation*, New York, NY: Basic Books, 1984.
[17] Michael J. Prietula, Kathleen M. Carley, and Les Glasser, *Simulating Organizations: Computational Models of Institutions and Groups*, Cambridge, MA: The MIT Press, 1998.
[18] Nigel Gilbert and Klaus G. Troitzsch, *Simulation for the Social Scientist*, Buckingham, UK: Open University Press, 1999.
[19] Herb Gintis, *Game Theory Evolving*, Princeton, NJ: The Princeton University Press, 2000.
[20] W. Brian Arthur, S. N. Durlauf, and D. Lane (eds.), *The Economy as an Evolving Complex System II*, SFI Studies in the Sciences of Complexity, Volume XXVII, Reading, MA: Addison Wesley, 1997.
[21] Leigh Tesfatsion (Guest Editor), Special Issue on Agent-Based Computational Economics, *Journal of Economic Dynamics and Control*, Volume 25, Numbers 3-4, March 2001.
[22] Leigh Tesfatsion (Guest Editor), Special Issue on Agent-Based Computational Economics, *Computational Economics*, Volume 18, Number 1, October 2001.

BIOGRAPHY

Leigh Tesfatsion received the Ph.D. in Economics, with a minor in mathematics, from the University of Minnesota, Minneapolis, in 1975. She is currently Professor of Economics at Iowa State University, with a courtesy appointment as Professor of Mathematics. Her recent research has focused on agent-based computational economics (ACE), the computational study of economies modelled as evolving systems of autonomous interacting agents. She is applying the ACE methodology to the study of market power in labor markets and to the study of restructuring in electricity markets. She currently serves as co-editor in charge of the Complexity-at-Large section of the journal *Complexity* as well as associate editor for the *Journal of Economic Dynamics and Control*, the *Journal of Public Economic Theory*, the *IEEE Transactions on Evolutionary Computation*, and *Applied Mathematics and Computation*.

LEIGH TESFATSION, *Guest Editor*
Department of Economics
Iowa State University
Ames, Iowa 50011-1070
http://www.econ.iastate.edu/tesfatsi/
email: tesfatsi@iastate.edu