Perspective

Economic agents and markets as emergent phenomena

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An overview of recent work in agent-based computational economics is provided, with a stress on the research areas highlighted in the National Academy of Sciences Sackler Colloquium session ''Economic Agents and Markets as Emergent Phenomena'' held in October 2001.

Decentralized market economies are complex adaptive systems consisting of large numbers of buyers and sellers involved in massively parallel local interactions. These local interactions give rise to macroeconomic regularities such as shared market protocols and behavioral norms which, in turn, feed back into the determination of local interactions. The result is a complicated dynamic system of recurrent causal chains connecting individual behaviors, interaction networks, and social welfare outcomes.

This intricate two-way feedback between microstructure and macrostructure has been recognized within economics for a very long time (1–3). Nevertheless, for much of this time, economists have lacked the means to model this feedback quantitatively in its full dynamic complexity. The most salient characteristic of traditional quantitative economic models supported by microfoundations has been their top-down construction. Heavy reliance is placed on extraneous coordination devices such as fixed decision rules, common knowledge assumptions, representative agents, and imposed market equilibrium constraints. Face-to-face personal interactions typically play no role or appear in the form of tightly constrained game interactions. In short, agents in these models have had little room to breathe.

Slowly but surely, however, advances in modeling tools have been enlarging the possibility set for economists (4–6). Researchers now can study a wide variety of complex phenomena associated with decentralized market economies, such as inductive learning, imperfect competition, trade network formation, and the open-ended coevolution of individual behaviors and economic institutions.

One branch of this work has come to be known as *agent-based computational economics* (ACE), the computational study of economies modeled as evolving systems of autonomous interacting agents.[†] ACE researchers generally rely on computational laboratories[‡] to study the evolution of decentralized market economies under controlled experimental conditions.

As in a culture-dish laboratory experiment, the ACE modeller starts by constructing an economy with an initial population of agents. These agents include both economic agents (e.g., buyers, sellers, dealers, etc.) and agents representing various other social and environmental phenomena (e.g., government, land, weather, etc.). The ACE modeller specifies the initial state of the economy by specifying the initial attributes of the agents. The initial attributes of an agent might include type characteristics, internalized behavioral norms, internal modes of behavior (including modes of communication and learning), and internally stored information about itself and other agents. The economy then evolves over time without further intervention from the modeller. All events that subsequently occur must arise from the historical time-line of agent–agent interactions. No extraneous coordination devices are permitted. For example, no resort can be made to the off-line determination and imposition of market-clearing prices through fixed-point calculations.

A special session highlighting ACE-related research, titled ''Economic Agents and Markets as Emergent Phenomena,'' was held as part of the NAS Sackler Colloquium in October 2001. The papers prepared for this session focused on the replication of stylized facts for financial markets, the design of computational agents for automated markets, the emergence of a cross-cultural global market, and emergent regularity in human-subject auction experiments.

To set these papers within a broader context, the next section provides a brief overview of related ACE research areas and some of the key issues addressed.

ACE Research Areas

A diverse sampling of ACE research can be found in refs. 8–10. The topics addressed divide roughly into eight research areas: (*i*) learning and the embodied mind; (*ii*) evolution of norms; (*iii*) bottom-up modeling of market processes; (*iv*) network formation; (*v*) intra-firm organization; (*vi*) using ACE laboratories to test the design of market protocols; (*vii*) using ACE laboratories to test the design of computational agents for automated markets; and (*viii*) parallel experiments with real and computational agents.[§]

A key issue relevant for all research areas is how to model the minds of the computational agents who populate ACE frameworks. Should these minds be viewed as logic machines with appended data-filing cabinets, which is the traditional artificial intelligence viewpoint? Or, should they instead be viewed as controllers for embodied activity, as advocated by evolutionary psychologists? If the focus of an ACE study is the design of a fully automated market, there is no particular reason why the minds of the computational agents should have to mimic those of real people—indeed, this could be positively detrimental to good market performance. On the other hand, if the focus is on the modeling of some real-world economic process with human participants, then mimicry might be essential to ensure predictive content.

A key issue relevant for research areas *ii* and *iii* is how mutual cooperation manages to evolve even when cheating reaps immediate gains and binding commitments are not possible. What roles do

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†See http://www.econ.iastate.edu/tesfatsi/ace.htm for extensive resources related to the ACE methodology.

‡The felicitous phrase ''computational laboratories'' is adopted from Dibble (7).

§A website providing a list of key issues, readings, and pointers to software, individual researchers, and research groups for many of these ACE research areas can be found at http://www.econ.iastate.edu/tesfatsi/aapplic.htm.

reputation, trust, reciprocity, retaliation, spitefulness, and punishment play? More generally, how do exchange protocols and other socially accepted rules of behavior come to be established in market contexts, and how stable are these rules over time? Are these behavioral rules diffusing across traditional political and cultural boundaries (commercial globalization), resulting in an increasingly homogeneous world?

Finally, a key issue for research area *iv* is the extent to which interaction networks are important for predicting market outcomes. If interaction effects are weak, as in some auction markets, then the structural aspects of the market (e.g., numbers of buyers and sellers, costs, capacities) will be the primary determinants of market outcomes. In this case, each different market structure should map into a relatively simple *central-tendency* output distribution that can easily be recovered by observing empirically or experimentally determined market outcomes in response to varying structural conditions. If interaction effects are strong, as in labor markets, then each different market structure might map into a *spectral* distribution of possible market outcomes, with outcomes clustered around two or more distinct "attractors" corresponding to distinct possible interaction networks.

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