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Agent-Based Computational Economics

How the idea originated and where it is going

Shu-Heng Chen

Routledge

Agent-Based Computational Economics

This book aims to answer two questions that are fundamental to the study of agent-based economic models: what is agent-based computational economics and why do we need agent-based economic modeling? This book provides a review of the development of agent-based computational economics (ACE) from the perspective of how artificial economic agents are designed under the influences of complex sciences, experimental economics, artificial intelligence, evolutionary biology, psychology, anthropology, and neuroscience.

The book begins with a historical review of ACE by tracing its origins. From a modeling viewpoint, ACE brings truly decentralized procedures into market analysis, from a single market to the whole economy. The book also reviews how experimental economics and artificial intelligence have shaped the development of ACE. For the former, it discusses how ACE models can be used to analyse the economic consequences of cognitive capacity, personality, and cultural inheritance. For the latter, the book covers the various tools used to construct artificial adaptive agents, including reinforcement learning, fuzzy decision rules, neural networks, and evolutionary computation.

This book will be of interest to graduate students researching computational economics, experimental economics, behavioural economics, and research methodology.

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How the idea originated and where it is going

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Preface

The idea of this book is to review the development of agent-based modeling in economics from a perspective that the author considers most generic. It is, therefore, not a survey of the application domains of agent-based modeling in economics, which itself can be a subject of interest, but now also becomes difficult given its quick expansion. The perspective taken in this book centers on *the idea of using agents as a bottom-up design for the study of emergent complexity*. The book takes John von Neumann's contribution to cellular automata as a starting point to see how this idea grows and evolves; in particular, how the use and hence the design of agents changes after constant interactions with other disciplines: computer science, artificial intelligence, experimental economics, behavioral economics, evolutionary economics, and econometrics. These constant interactions enrich the design of agents with the coexistence of several different principles, from the original simple design to more complex and intelligent design. They will be presented in this book with various illustrations from agent-based macroeconomic models to agent-based microeconomic models, from artificial financial markets to evolution of technology. This perspective, while it may be narrow, is focused enough to distinguish this book from other similar work in the literature.

The plan of the book began in May, 2008, when the author was generously invited by Prof. Kumaraswamy Velupillai to the University of Trento to give a two-day workshop on agent-based modeling in economics and finance. The skeleton of the book emerged as a preparation for the workshop. During the workshop, the author further benefited from discussions with Stefano Zambelli, Charlotte Bruun, Francesco Luna, and Stephen Kinsella, which helped grow many fine details. In fact, they are all experts on agent-based modeling in economics, although the skeleton of the book is not extensive enough to accommodate all of their contributions in this area.

From October to November 2009, the author was honorably invited as a visiting professor to Trento to give a course on Heterogeneous and Multi-Agent Modeling in Economics for the second-year PhD students at the Interdepartmental Centre for Research Training in Economics and Management (CIFREM). The lecture was given in a very interactive and stimulating environment. Prof. Kumaraswamy Velupillai attended all of my lectures, and encouraged me to prepare my lecture into a book format, generously inviting me to submit a book proposal for his editing series on Routledge Advances in Experimental and Computable Economics. This invitation gave the author the impetus to start a book project.

Around this time and in the following years, the author was luckily invited to give tutorials in summer schools or plenary speeches in international conferences. These invitations provided the author further momentum to carry out the book project, to lecture on some preliminary versions of the book and, most importantly, to receive feedback from audiences. These events were:

- The First Chinese Forum on Intelligent Finance, Chinese Academy of Sciences, Beijing, China, February 26–28, 2009.
- The Summer School of the 15th International Conference Computing in Economics and Finance, University of Technology, Sydney, Australia, July 14, 2009.
- The Central European University Summer School on Complex Systems and Social Simulations, Budapest, Hungary, July 23, 2009.
- APCTP (Asia Pacific Center for Theoretical Physics) School on Econophysics, Pohang, Korea, August 24–27, 2009.
- Facing Crisis: International Seminar on How to Develop Methods of Economic Research, Beijing, China, September 10–11, 2009.
- International Conference on How and Why Economists and Philosophers Do Experiments: Dialogue between Experimental Economics and Experimental Philosophy, Kyoto Sangyo University, Kyoto, Japan, March 27–28, 2010.
- Sino-foreign-interchange Workshop on Intelligence Science and Intelligent Data Engineering, Harbin, China, June 3–5, 2010.
- The 16th International Conference on Computing in Economics and Finance, City University London, UK, July 13–17, 2010.
- The Second Edition of the International Workshop on Managing Financial Instability in Capitalist Economies (MAFIN 2010), Reykjavik University, Reykjavik, Iceland, September 23–25, 2010.
- Conference on Quantitative Behavioral Finance, University of Nice Sophia Antipolis, Nice, France, December 8–10, 2010.
- First Workshop on Quantitative Finance and Economics, International Christian University, Tokyo, February 21–23, 2011.
- International Conference on Nonlinear Economic Dynamics and Financial Market, South China Normal University and Guangzhou University, Guangzhou, China, March 31–April 2, 2011.
- Third International Conference on Econophysics and Summer School on Teaching and Enterprise, Department of Physics and School of Science, Loughborough University, UK, September 24–29, 2011.
- Lecture Series on Agent-Based Computational Economics: A Historical and Interdisciplinary Review, School of Management, Harbin Institute of Technology, Harbin, China, November 7–9, 2011.
- Third International Workshop on Managing Financial Instability in Capitalist Economies, Genoa, Italy, September 19–21, 2012.

– The Fifth Edition of Epistemological Perspectives on Simulation, Trinity University, San Antonio, Texas, October 10–12, 2012.
– Workshop on Computational Finance and Economics, Mexican Central Bank, Mexico City, Mexico, October 17, 2012.
– Eleventh International Conference of Socionetwork Strategies: Understanding Complex Society from Agent-Based Simulation, Research Institute for Socionetwork Strategies, Kansai University, Osaka, Japan, February 27, 2014.
– Fifth World Congress on Social Simulation, São Paulo, Brazil, November 4–7, 2014.
– First Cross-Straits Symposium on Economic Frontier and Policy Simulation in China, China Southern Normal University, Guangzhou, China, November 15–16, 2014.

The author is greateful to Heping Pan, Carl Chiarella, Xue-Zhong (Tony) He, George Kampis, László Gulyás, Guocheng Wang, Sobei Oda, Lei Xu, Wei Zhao, Giulia Iori, Marco Raberto, Seunghwan Kim, Woo-Sung Jung, Gabjin Oh, Jorgen Vitting Andersen, Taisei Kaizoji, Mauro Politi, Duo Wang, Fahuai Yi, Feodor Kusmartsev, Zhong-Yu Wang, Silvano Cincotti, Yu Zhang, Dante Suarez, Alexandrova Kabadjova Biliana, Edward Tseng, Kazuhito Ogawa, Jaime Sichman, Zhiqiang Dong, and Lianqing Peng for their generous invitations and kind arrangement.

The book in its manuscript form has been used as lecture materials for a one-semester course given at the Master of Finance Program in Tianjin University, in years 2012 and 2014. This class probably has the most devoted students in China. The teaching experience in this class is challenging but breathtaking. The book has substantial context on the natural allied relationship between agent-based computational economics and experimental economics. The leadership of Wei Zhang has helped Tianjin University build the strongest academic environment for this new research paradigm. On this occasion, the author is particularly grateful to Wei Zhang and his colleagues at College and Management and Economics, including Xiong Xiong, Yongjie Zhang, Da Ren, Xu Feng, Dehua Shen, and many others, for providing the author with a very stimulating and inspiring research-oriented teaching environment.

While writing the book, the author witnessed and was accompanied by the fast-growing agent-based communities in both economics and social sciences. The author constantly benefited from participation at some major events organized by the Society for Computational Economics, the Society for Economic Science with Heterogeneous Agents, the NYC Computational Economics and Complexity Workshop, the Pan-Asian Association for Agent-based Approach in Social Systems Sciences, the International Foundation for Autonomous Agents and Multiagent Systems, the Computational Social Science Society of the Americas, the IEEE Computational Intelligence Society, and the Asia-Pacific Econophysics Conference. The author would like to give thanks to a number of active members who have not just helped the author to learn this subject, but also contributed themselves to the shining history of the communities. In addition to those who have already been mentioned above, they are David Kendrick, Leigh Tesfatsion, Thomas Lux, Jasmina Arifovic, Robert Marks, Hans Amman, Blake LeBaron, Barkley Rosser, Alan Kirman, Herbert Dawid, Cars Hommes, Nick Vriend, John Duffy, Robert Axtell, Frank Westerhoff, Giovanni Dosi, Maruo Gallegati, Domenico Delli Gatti, Massimo Ricottilli, Pietro Terna, Jason Barr, Troy Tassier, Leanne Ussher, Chris Ruebeck, Alan Isaac, Myong-Hun Chang, Andreas Pape, Nigel Gilbert, Claudio Cioffi-Revilla, William Griffin, David Sallach, Bruce Edmonds, Scott Moss, William Rand, William Lawless, Flaminio Squazzoni, Van Dyke Parunak, Akira Namatame, Yuji Aruka, Hiroshi Deguchi, Takao Terano, Shingo Takahashi, Aki-Hiro Sato, and Siew Ann Cheong.

The book was mainly written at the AI-ECON Research Center, National Chengchi University. The center is one of most active research units in promoting agent-based computational economics. The author is very blessed by being surrounded by many supportive colleagues, students, post-docs, and visitors. Many of them became co-authors in a number of the author's other projects. Here, acknowledgements are specifically given to Shu G. Wang, Wei-Lin Mao, Chu-Chia Lin, Chung-Ming Kuan, Been-Lon Chen, Mei-Lie Chu, Yih-Chyi Chuang, Sun-Chong Wang, Sai-Ping Li, Chen-Yuan Tung, Nai-Shing Yen, Reuy-Ming Liao, Lee-Xieng Yang, Ray-May Hsung, Chia-Hsuan Yeh, Wo-Chiang Lee, Wei-Yuan Lin, Chueh-Yung Tsao, Tzu-Wen Kuo, Ya-Chi Huang, Bin-Tzong Chie, Chung-Ching Tai, Chia-Ling Chang, Hung-Wen Lin, Ye-Rong Du, Chia-Yang Lin, Ying-Fang Kao, Nicolas Navet, Tina Yu, Tong Zhang, Michael Kampouridis, Tong-Kui Yu, Jie-Jun Tseng, Tzai-Der Wang, Kuo-Chuan Shih, Umberto Gostoli, and Ragupathy Venkatachalam. I am in great debt to them and to my family, without whom it would have been impossible to complete the book. Finally, I am grateful to Lisa Thomson and Routledge's professional editing team for being so supportive and helping me accomplish the last mile of the book.

Shu-Heng Chen
March 15, 2015

Part I

Ideas and structures of the book

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1 Economics in an interdisciplinary context

Humans are heterogeneous in many ways. Nothing can be more evident than this simple fact. Yet, in mainstream economics, the device of the homogeneous agent or, more formally, the *representative agent*, has been employed for quite a long, yet uneasy, period of time. Psychologists, on the other hand, have acknowledged the heterogeneity of agents right from the beginning. Various developments in psychometric testing simply show us that humans are empirically different. They are not just bounded rational; they are heterogeneous in cognitive capacity as well as personality. Moreover, anthropologists and sociologists show us that, when put in a social context, they are under different sets of beliefs or norms. From the viewpoint of genetic biology, some human heterogeneities are inherited from parents or ancestors. Nevertheless, mainstream economics has long been silent on all of these *human factors*, assuming that they are not *economically sensible*. The empirical evidence accumulated in recent years, however, shows the significance of cognitive capacity, personality, emotion, cultural inheritance, and social norms, from micro to macro. Nevertheless, the modeling techniques which can incorporate agents who are heterogeneous in these dimensions and demonstrate the emergent aggregate behavior through their interactions are less well established in economics.

The purpose of this book is to place the study of economics in an interdisciplinary framework so that the underlying mathematical or computational modeling can be grounded in various kinds of empirical evidence ranging from genetic biology to neural sciences, sociology, psychology, and, of course, experimental economics. In fact, this interdisciplinary modeling has already existed by different names among people with different backgrounds. For people with a conventional economics, psychology, or mathematics background, its familiar name is *behavioral economics*; for people with a mixed background of economics and computer sciences or computer engineering, its familiar name is *agent-based computational economics*; for the recent immigrants from physics to their "colony" in economics, it is called *econophysics*. Each of its names represents an origin of its development. Behavioral and econophysic modeling is more analytically demanding, whereas agent-based computational economic modeling is computationally intensive.

Regardless of different names, models with these tags and origins share a great common feature, i.e., they can each replace the conventional representative agent

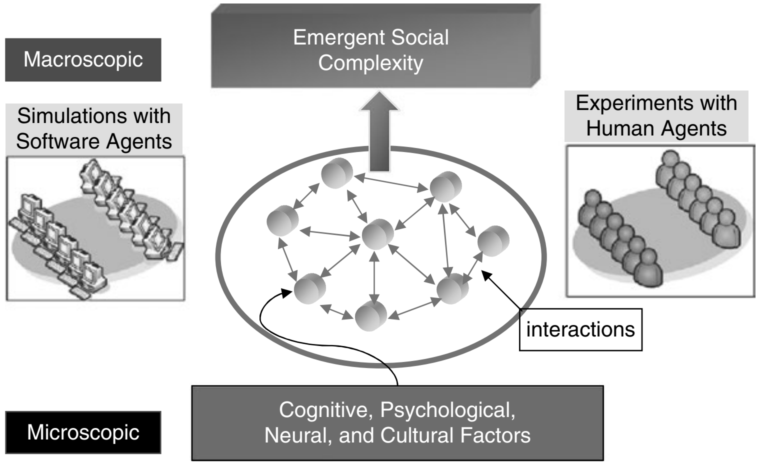

Figure 1.1 Microfoundations and macroeconomics.

Source: Adapted from Chen and Wang (2011), Figure 2.

model and provide an alternative *microfoundation*. Figure 1.1 shows this common feature. We will come back to this figure and elaborate on its essence in Section 1.1. Here, we only provide a brief list to exemplify the microfoundational work already done in each of the three research areas.

Behavioral macroeconomics

There is a series of works on behavioral macroeconomics by George Akerlof, the 2001 Nobel Laureate in Economics. The most notable features of this are his Nobel Prize lecture (Akerlof, 2002), his American Economic Association Presidential address (Akerlof, 2007), and his advice on the current financial tsunami (Akerlof and Shiller, 2009). This series can be augmented by a number of macroeconomic laboratory experiments (Duffy, 2009).

Agent-based computational economics

Agent-based computational economics, almost since its beginning, has been devoted to the study of macroeconomic issues. Leigh Tesfatsion, on her Iowa State University web page, http://www.econ.iastate.edu/tesfatsi/amulmark.htm, has a collection of these studies. Among them, Chen (2003), Delli Gatti *et al.* (2008), LeBaron and Tesfatsion (2008), and Delli Gatti *et al.* (2011) provide various illustrations with different motives. Due to the financial crisis which occurred in 2008–2009, attention has been paid to agent-based computational economic modeling as an alternative approach to maintaining better tabs on the increasingly complex and intertwined economy (Buchanan, 2009; Farmer and Foley, 2009). In addition, a series of conferences were organized in the year 2010 to reflect on the crises in economic theory with regard to the economic crisis of 2007–2009. In 2009, George Soros pledged to give 50 million dollars over ten years to set up the Institute of New Economic Thinking as a reaction to his feeling that "false theory" has resulted in tremendous damage to the world economy. Agent-based economic modeling is considered to be a candidate for an alternative.

Econophysics

In physics, during the late nineteenth century a fundamentally new approach referred to as *statistical mechanics* was advanced by James Maxwell (1831–1879), Ludwig Boltzmann (1844–1906), Josiah Gibbs (1839–1903), and others. This approach, which significantly contributed to the study of molecular dynamics, was also formally introduced to the study of economics and even the social sciences in the 1990s.[1] This new field is broadly known as *econophysics* or *sociophysics*.[2] An econophysics approach to macroeconomics can be exemplified by a series of work done by Masano Aoki (Aoki, 1996, 2002a; Aoki and Yoshikawa, 2006).

1.1 The interdisciplinary framework

Figure 1.1 has all the ideas to be included in this book, albeit expressed in a highly simplified way. Let us start with the middle part of the figure, which intends to picture *a system of interacting agents*.[3] For a physicist, this picture may be read as a *particle system*, with two important departures:

Heterogeneous agents

First, agents (particles) are not homogeneous; instead, they are heterogeneous. Abandoning the device of the representative agent is exactly the concept conveyed at the beginning of this book. In Part VI, we will provide corroborative evidence and discussions as to why heterogeneous agents should not be viewed as an exception but as a rule in the future of economic modeling.

Interactions

Second, the relations among the agents (particles) are not just random bumping but *social* in the sense that these agents mutually *influence* each other, so that their behaviors change along with these interaction processes. These agents are, in general, not independent. This feature allows us to accommodate concerns from anthropology, religion, culture, sociobiology, and evolutionary psychology.

Social networks

Although the interactions among agents can be erratic, they may not be entirely random. Implicitly or explicitly, the interactions take place through social networks. The topologies of social networks can be another crucial factor for the interactions, and the topologies, in general, are endogenously determined.

Homo sapiens

Let us move to the bottom of Figure 1.1, which describes these individual agents. In conventional economics, the description of the agents is simple: *Homo economicus* or economic man. They are identically infinitely smart, hyperrational, self-interested, unemotional, and utility-maximizing agents. While these creature have been surviving in mainstream economics for decades, economists are now becoming more interested in knowing *Homo sapiens*—emotional beings (Thaler, 2000).[4] This broader interest has brought about significant growth in interdisciplinary engagement between economists and other social scientists or even scientists. Psychology and computer science both come into play from this side.

Psychological fundamentals

On the one hand, we certainly hope to give a more realistic description of the human agents by at least not missing their essential dimensions; on the other hand, we want to make this description programmable. The former motivates an increasing number of economists to learn from psychologists and coherently ties economics and psychology in an unprecedented way. This interdisciplinary collaboration between the two has also promoted a new subfamily in economics, namely *behavioral economics*. Economists are now more alert to the social consequences of widely documented agents' behavioral *biases*. More recently, psychology has helped economists to reshape a proper definition or representation of an individual economic agent. A series of recent studies indicates that *cognitive capacity* (the intelligence quotient) and *personality* are two important missing elements in conventional characterizations of economic agents. In fact, these two human factors should be thought of as the *fundamentals* of the economy; they are certainly more concrete than *preference*, a very controversial idea, both historically and currently.

Artificial agents

We program the artificial agents to reflect various kinds of psychological fundamentals, behavioral rules, or behavioral biases. Artificial agents is not a term commonly used in behavioral economics, although all the models inevitably start with some artificial agents. The whole of Part III is devoted to this construct, but most materials introduced there were produced in the earlier stages of agent-based computational economics when it was still distinct from behavioral economics. In agent-based computational economics the focus of artificial agents is on learning, whereas in behavioral economics the focus is on preference and utility. In the future, the gap between the two will be narrowed as *behavioral agent-based computational economic models* are gradually developed. Chapter 19 presents one case in point.[5]

1.2 Organization of the book

Normally, the table of contents of a book suggests that the reader can read the book in a sequential order. While the table of contents must be unique, that kind of suggestion is not. Therefore, in this section, we elaborate on the organization of the book and suggest some alternative tables of contents which could be used by different readers with different purposes or different pursuits.

1.2.1 Two fundamental questions

The book tries to answer two questions which we consider to be quite fundamental to the study of agent-based economic models, namely, *what* and *why*? What is agent-based computational economics? Why do we need agent-based economic modeling of the economy? These two questions are generally shared by other social scientists who are also interested in agent-based modeling. Therefore, they are better addressed in a broader background, i.e., *agent-based computational social sciences*. To answer the first question, it would be nice if we could start with some very simple agent-based social or economic models which, however, all have the essences of agent-based models. Chapter 4 serves this purpose. It is mainly composed of the three simplest agent-based social models, namely *Schelling's Segregation Model*, *Conway's Game of Life*, and *Wolfram's Edge of Chaos*. This chapter can help beginners to quickly grasp what an agent-based social model is.

The most direct way to address the second question is to ask whether we can have a collection of successful agent-based models in the social sciences. By success, we mean that these models are capable of explaining or predicting some social phenomena which are hard to capture using the conventional models of the respective disciplines or are able to provide new insights. While we cannot be absolutely sure what these models are, Chapter 2 does make such an attempt. In addition to that, Epstein (2008) provides a long list of answers to the issues involved, and in Chapter 2 we shall review some of them.

1.2.2 Novelty discovery: toward autonomous agents

The book will start with a concrete example of agent-based (economic) modeling, namely *cellular automata* (Chapter 4). The reason we choose cellular automata as our kick-off example is partially because we consider *a model of agents* to be the first part of agent-based modeling. However, to clearly indicate our departure from *Homo economicus* to *Homo sapiens*, we would like to provide a simple historical background on the development of economic agents in economics; specifically, from *algorithmic (behavioral) agents* to *autonomous agents* (Chapter 5). This will quickly lead us to see that part of the economic agents is defined by the associated algorithms. In fact, Chapters 5 to 7 provide many more illustrations on the algorithmic aspects of economic agents, as they are called algorithmic agents.

Autonomous agents are first exemplified in Chapter 6 via an artificial intelligence tool called genetic programming (GP), while the foundation work for autonomous agents is not given until later in Part IV. This line of exposition is then further extended to Chapter 8. Chapter 8 can be read together with Section 14.5 and Part VIII, and are all concerned with a central theme of the book, which I shall refer to as *the legacy of Marshall*. Together they demonstrate one unique feature of agent-based modeling, i.e., its capability of modeling *intrinsically constant changes*. One essential ingredient of triggering constant change is equipping agents with a *novelty-discovering* or *chance-discovering* capability so that they may constantly exploit the surrounding environment, which causes the surrounding environment to act or react, and hence change constantly.

1.2.3 Microstructure dynamics

If economics is about constant change, and that happens because autonomous agents keep on searching for chance and novelties, then change in each individual and change in the microstructures must accompany the holistic picture of constant change. A number of chapters in this book attempt to have *microstructure dynamics* as their focus. Part V illustrates the rich microstructure dynamics in agent-based financial markets. Chapter 14 is mainly devoted to the study of microstructure dynamics in light of the *statistical mechanical approach* (Section 14.4). With this approach, the set of behaviors or strategies is finite or bounded. A finite set allows us to study the microstructure dynamics on solid ground, but it inevitably implies the absence of novelties and their discovery, which is the other focus of the book. Section 15.4, therefore, extends the analysis of the microstructure dynamics into an infinite set so that rich microstructure dynamics are embedded within the novelty-discovering processes.

These chapters are connected by two hypotheses, namely the *market fraction hypothesis* in Chapter 14 and the *dinosaurs hypothesis* in Section 15.4. The two hypotheses are further connected by using genetic programming to formulate and test them (Section 15.4).

1.2.4 Agent engineering

A large part of the book is concerned with the design of software agents used in agent-based modeling. In general, this task is known as *agent engineering*. On the one hand, the book reviews a number of tools which have been used to design agents with different degrees of sophistication; on the other hand, the book also addresses how to use these tools properly. The latter subject involves the empirical grounds of agent engineering. The behavior of human agents observed in experimental economics provides one empirical ground. Using this empirical ground to build software agents naturally ties software-agent simulations and human-agent experiments together.

The tools used to build software agents are mainly introduced in Part IV, which covers reinforcement learning (Chapter 10), artificial neural networks (Chapter 12), and evolutionary computation (Chapter 13). In this repertoire, do agents follow reinforcement learning to learn? Or do they learn as predicted by artificial neural networks? When is evolutionary computation a more sensible description of learning? A number of chapters contribute to the study of these issues. Chapter 7 is concerned with the idea of *calibrating artificial agents* using data from human-subject experiments. Similar to Chapter 7, Chapter 16 introduces work using real data (field data) to estimate the parametric behavioral rules, and is not necessarily restricted to learning.

1.2.5 Experimental economics

A large part of the book is also written to reflect the intertwined connection between experimental economics (EE) and agent-based computational economics (ACE). Several different developments of algorithmic agents are all inspired or related to experimental economics. The double auction (DA) market (Chapter 8) is probably the most illuminating illustration of the connection between agent-based computational economics and experimental economics. Having said that, we notice that the DA market is the context in which various versions of agents, crossing both realms of EE and ACE, have been proposed. The motivation behind inventing *zero-intelligence agents* consists of replicating the market behavior observed in the double auction market experiments (Section 8.3). The *programmed agents* or *human-written agents* are part of the tournament-like offline experiments (Section 9.2). The idea of *calibrated agents* is first introduced to replicate human choice behavior in the multi-armed bandit experiment (Chapter 7). Finally, autonomous agents are also inspired by both online and offline human experiments in double auction markets (Sections 9.3 and 9.4). Needless to say, the idea of algorithmic agents is enriched by interaction with observations from experimental economics.

1.2.6 Econophysics

It is fair to say that agent-based modeling was first used by physicists, though known by different names, including cellular automata, the kinetic model, percolation model, Ising model, etc. The recent massive economic and financial applications of these models by physicists have contributed to a significant part of the field known as *econophysics* (Chen and Li, 2012). In Chapter 4, we present the *cellular automata tradition* of ACE. The tradition initiated by von Neumann (1903–1957; von Neumann, 1966) is then passed on to Thomas Schelling (Schelling, 1978), John Conway, Stephen Wolfram (Wolfram, 1994), Peter Albin (1934–2005; Albin, 1975, 1998), Duncan Foley, Joshua Epstein, and Robert Axtell (Epstein and Axtell, 1996), and further down to the arising of the spatial agent-based models extensively applied in geography, city planning, and ecology. This series of literature enables us to see the connection between the particle system in physics and agent-based modeling in economics. They together serve as a gateway leading to the current development of complex science and the later more general development of complex networks (Chapter 22).

Econophysics, in spirit, also concurs with the *randomization approach* or the *maximum entropy approach* in agent-based modeling (Section 8.5.1). The capability of this approach to replicate complex financial dynamics systems shows that some aggregate phenomena generated from human-agent systems with the complex motives and behavioral rules of humans can be rather well approximated by a system with rather simple agents characterized by simple motives and simple rules. In a sense, it indicates that adding more complex strategies to the agent-based models may have little by way of macroscopic effect since these complex strategies may interact in such a way that they mutually annihilate each others' forces. It is this possibility that prompts us to think about a general physical system which is equipped with the most rudimentary forces but can overarch several seemingly unrelated social phenomena, for example from pedestrian counterflow, the Schelling segregation model (Vinkovic and Kirman, 2006), the El Farol Bar problem (minority games), and then to financial markets.[6]

Notes

1 What may interest both economists and physicists is that the early study of molecules in physics was motivated by observing interactions among humans (Ball, 2006).

2 Galam (2004) gives a personal account of the origin of sociophysics, but a more interesting and even earlier review of the interdisciplinary relation between classical physics and classical economics was documented by Cottrell *et al.* (2009).

3 The size of the system, which can be another important consideration in this book, does not have to be as small or finite as the one drawn here.

4 Thaler (2000) particularly characterizes the shift in the interest by distinguishing the *normative* description of human behavior from the *positive* description of human behavior.

5 Nonetheless, there is another major difference which we would like to point out here, i.e., heterogeneity. Despite the findings of so many *anomalies*, behavioral economics does not necessarily resist the device of a representative agent. In fact, the device of the representative agent is still extensively used in various behavioral economic models, in particular, behavioral macroeconomics, since that may make it easier for us to present the aggregate consequence of a certain class of behavioral biases by not *averaging them out*. For example, Stracca (2004) states that "what matters for aggregate market prices is the behavior of the representative agent, so we do not have to care, in principle, about behavioral biases that cancel out in the aggregate" (p. 378). However, neoclassical economics used to consider exactly the opposite, namely, these biases will cancel each other out when being summed up. Therefore, it seems important to *show*, rather than to *assume*, that these biases will not go away in the aggregates. For that reason, we believe that *heterogeneous behavioral economic models* should be more persuasive than the homogeneous ones, or, naturally, be the next step or the extension of the latter (Thaler, 2000).

6 It is possible to simulate the financial time series using *social force models for pedestrian dynamics* (Parisi, 2010). The social force model is one kind of agent-based model which is not much different from the particle system in physics. The agents (particles) in this system have simple objectives and follow simple rules.

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