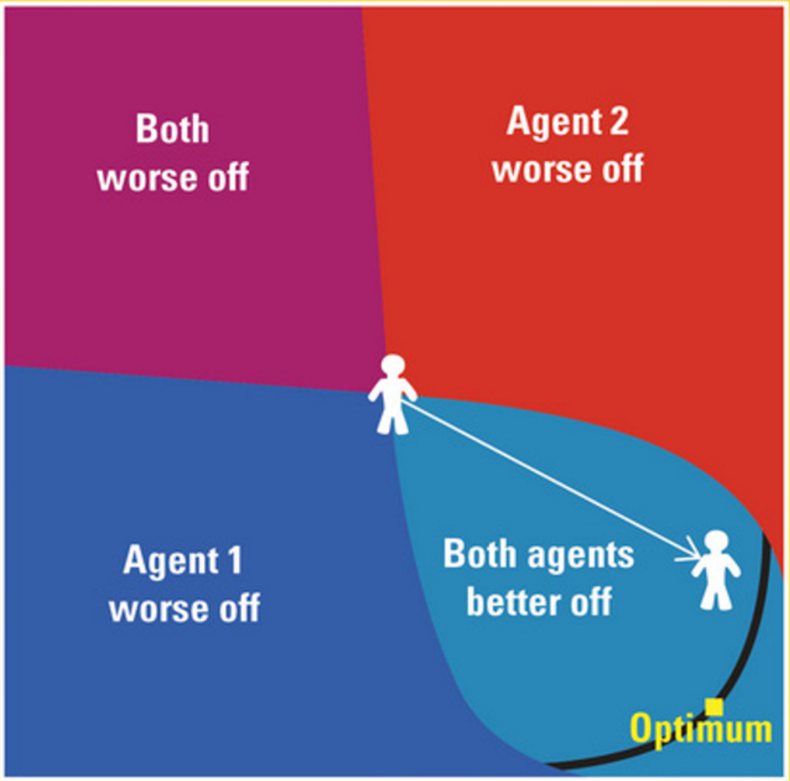
Agent-Based Modelling in Economics

Lynne Hamill • Nigel Gilbert



WILEY

Agent-Based Modelling in Economics

Agent-Based Modelling in Economics

Lynne Hamill and Nigel Gilbert

Centre for Research in Social Simulation (CRESS),
University of Surrey, UK

WILEY

This edition first published 2016

Registered Office
John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

Library of Congress Cataloging-in-Publication data applied for

ISBN: 9781118456071

A catalogue record for this book is available from the British Library.

Set in 9/11pt Times by SPi Global, Pondicherry, India

1 2016

Contents

Preface

This book is an introduction to the power of using agent-based modelling (ABM) in economics. This is sometimes referred to as multi-agent modelling and in the context of economics, ACE, standing for Agent-based Computational Economics.

The book takes some of the usual topics covered in an undergraduate economics textbook and demonstrates how ABM can complement more traditional approaches to economic modelling and better link the micro and the macro.

This book is designed to appeal to:

- Trained economists who want an introduction to ABM
- Masters and doctoral students and researchers considering using ABM in their research
- Students in their third year of undergraduate study, either as the primary reading for a self-contained module on simulation approaches or as a starting point for an undergraduate dissertation.

We expect that most readers will be familiar with the basics of standard economics, up to the equivalent of a second-year undergraduate, but throughout, we give pointers to where more background can be found.

Thanks to colleagues in CRESS – Jen Badham, Tina Balke and Peter Johnson – and to Paul Levine and Creighton Redman.

Copyright notices

1

Why agent-based modelling is useful for economists

1.1 Introduction

This book provides an introduction to the power of using agent-based modelling (ABM) in economics. (ABM is sometimes referred to as multi-agent modelling and, in the context of economics, agent-based computational economics (ACE)). It takes some of the usual topics covered in undergraduate economics and demonstrates how ABM can complement more traditional approaches to economic modelling and better link the micro and the macro.

This chapter starts with a brief review of the history of economic modelling to set the context. There follows an outline of ABM: how it works and its strengths. Finally, we set out the plan for the rest of the book.

1.2 A very brief history of economic modelling

> The Method I take to do this, is not yet very usual; for instead of using only comparative and superlative Words, and intellectual Arguments, I have taken the course (as a Specimen of the Political Arithmetick I have long aimed at) to express my self in Terms of Number, Weight, or Measure; to use only Arguments of Sense, and to consider only such Causes, as have visible Foundations in Nature.
>
> Sir William Petty (1690)

Whether Sir William Petty was the first economic modeller is arguable. Was Quesnay's *Tableau Economique* dated 1767 the first macroeconomic model? Or Ricardo's 1821 model of a farm the first microeconomic model? (Those interested in these early models should read Morgan,

Agent-Based Modelling in Economics, First Edition. Lynne Hamill and Nigel Gilbert.

2012, pp.3–8.) Nevertheless, books of political economy such as Smith's *Wealth of Nations* (1776) or Marshall's *Principles of Economics* (1920) had no modelling or mathematics. There is almost none in Keynes's *General Theory of Employment, Interest and Money* (1936).

Traditional macroeconomic models

For our purposes, we shall start with the macroeconomic models produced in the 1930s by Frisch and Tinbergen (Morgan, 2012, p.10). These models comprised a set of equations relying on correlations between time series generated from the national accounts. There was no formal link between these macroeconomic models and microeconomic analysis despite the traditional view that 'the laws of the aggregate depend of course upon the laws applying to individual cases' (Jevons, 1888, Chapter 3, para 20). Not all saw benefit in these new models. For example, Hayek (1931, p.5) wrote:

> …neither aggregates nor averages do act upon each other, and it will never be possible to establish necessary connections of cause and effect between them as we can between individual phenomena, individual prices, etc. I would even go as far as to assert that, from the very nature of economic theory, averages can never form a link in its reasoning.

Nevertheless, macroeconomics became identified as separate field from microeconomics with the publication of Samuelson's *Economics* in 1948 (Colander, 2006, p.52).

Dynamic stochastic general equilibrium models

The separation of macro- and microeconomics continued until the economic crisis of the mid-1970s prompted what is now known as the Lucas critique. In essence, Lucas (1976) pointed out that policy changes would change the way people behaved and thus the structure being modelled, and this meant that existing models could not be used to evaluate policy. The result was dynamic stochastic general equilibrium (DSGE) models that attempt 'to integrate macroeconomics with microeconomics by providing microeconomic foundations for macroeconomics' (Wickens, 2008, p.xiii). This integration is achieved by including 'a single individual who produces a good that can either be consumed or invested to increase future output and consumption' (Wickens, 2008, p.2). They are known as either the Ramsey (1928 and 1927) models or as the representative agent models. In effect, the representative agent represents an average person. And this average person bases their decision on optimisation. The limitations of using representative agents have been long recognised (e.g. by Kirman, 1992). But they have continued to be used because they make the analysis more tractable (Wickens, 2008, p.10). However, this is changing. Wickens noted in 2008 (2008, p.10) that 'more advanced treatments of macroeconomic problems often allow for heterogeneity', and the technical problems of using heterogeneous agents in DSGE models are now (in 2014) being addressed in cutting-edge research projects.

Complexity economics

Not all economists think that the DSGE models are the right way to proceed. For example, in 2006, Colander published *Post Walrasian Macroeconomics: Beyond the Dynamic Stochastic General Equilibrium Model*, a collection of papers that set out the agenda for an alternative approach to macroeconomics that did not make the restrictive assumptions found in DSGE models and in particular did not assume that people operated in an information-rich environment.

The DSGE approach assumes that the economy is capable of reaching and sustaining an equilibrium, although there is much debate about how equilibrium is defined. Others take the view that the economy is a non-linear, complex dynamic system which rarely, if ever, reaches equilibrium (see, e.g. Arthur, 2014). While in a linear system, macro level activity amounts to a simple adding up of the micro actions, in a non-linear system, something new may emerge. Arthur (1999) concluded:

> After two centuries of studying equilibria – static patterns that call for no further behavioral adjustments – economists are beginning to study the general emergence of structures and the unfolding of patterns in the economy. When viewed in out-of-equilibrium formation, economic patterns sometimes simplify into the simple static equilibria of standard economics. More often they are ever changing, showing perpetually novel behavior and emergent phenomena.

Furthermore, 'Complex dynamical systems full of non-linearities and sundry time lags have been completely beyond the state of the arts until rather recently', but 'agent-based simulations make it possible to investigate problems that Marshall and Keynes could only "talk" about' (Leijonhufvud, 2006). More recently, Stiglitz and Gallegati (2011) have pointed out that use of the representative agent 'rules out the possibility of the analysis of complex interactions'; and they 'advocate a bottom-up approach, where high-level (macroeconomic) systems may possess new and different properties than the low-level (microeconomic) systems on which they are based'. ABM is therefore seen by many as offering a way forward.

The impact of the 2008 economic crisis

Once again, it has taken an economic crisis to prompt a re-evaluation of economic modelling. Indeed, the 2008 economic crisis caused a crisis for economics as a discipline. It is now widely recognised that a new direction is needed and that ABM may provide that. Farmer and Foley (2009) argued in *Nature* that 'Agent-based models potentially present a way to model the financial economy as a complex system, as Keynes attempted to do, while taking human adaptation and learning into account, as Lucas advocated'. A year later, *The Economist* (2010) was asking if ABM can do better than 'conventional' models. Jean-Claude Trichet (2010), then president of the European Central Bank, spelt out what was needed:

> First, we have to think about how to characterise the *homo economicus* at the heart of any model. The atomistic, optimising agents underlying existing models do not capture behaviour during a crisis period. We need to deal better with heterogeneity across agents and the interaction among those heterogeneous agents. We need to entertain alternative motivations for economic choices. Behavioural economics draws on psychology to explain decisions made in crisis circumstances. Agent-based modelling dispenses with the optimisation assumption and allows for more complex interactions between agents. Such approaches are worthy of our attention.

The Review of the Monetary Policy Committee's Forecasting Capability for the Bank of England concluded that 'The financial crisis exposed virtually all major macro models as being woefully ill-equipped to understand the implications of this type of event' (Stockton, 2012, p.6). In early 2014, the United Kingdom's Economic and Social Research Council (ESRC) sponsored a conference on *Diversity in Macroeconomics*, subtitled *New Perspectives from Agent-Based Computational, Complexity and Behavioural Economics*, to bring together practitioners of the new approaches, mainstream academic economists and policymakers (Markose, 2014).

Furthermore, by 2013, the call for change had spread to the teaching of economics (*Economist*, 2013), and in 2014, *Curriculum Open-Access Resources in Economics* (CORE) was launched, providing an interactive online resource for a first course in economics, and it is planned to include agent-based simulations in this new way of teaching economics (CORE, 2014; Royal Economic Society, 2014).

So, what is ABM? We give an overview in the next section.

1.3 What is ABM?

The development of computational social simulation modelling started in the early 1960s with microsimulation (Gilbert & Troitzsch, 2005, p.6; Morgan, 2012, pp.301–315). Microsimulation takes a set of data about a population – of people, households or firms – and applies rules to reflect changes, enabling the modeller to look at the overall impact (Gilbert & Troitzsch, 2005, p.8). Such an approach is particularly useful for modelling policy changes, for example, to see who is made better or worse off by tax changes. However, although allowing for heterogeneity, microsimulation does not allow interaction. Only with the arrival of ABM did modelling interaction between agents become possible.

ABM grew out of research on non-linear dynamics and artificial intelligence and was facilitated by the arrival of personal computers in the 1980s and early 1990s. An agent-based model is a computer program that creates an artificial world of heterogeneous agents and enables investigation into how interactions between these agents, and between agents and other factors such as time and space, add up to form the patterns seen in the real world. The program creates agents located with different characteristics and tells them what they can do under different circumstances. Early work such as Epstein and Axtell's (1996) *Sugarscape* model demonstrated the potential power of this approach, and Squazzoni (2010) described what has been achieved since the mid-1990s.

Usually, an agent represents a person, but it can represent a household, a firm or even a nation, as we shall illustrate. Heterogeneity of agents is a key feature: each agent may have a unique set of characteristics and behaviour rules (Epstein, 2006, p.51). The agents are distributed across a space envisaged by the modeller which may represent a landscape or a social network or more abstract 'spaces' (Epstein, 2006, p.52). They may be distributed randomly across the whole space or according to some other principle. The space is typically two-dimensional and may have boundaries or be continuous.

The behaviour rules specify how agents interact with neighbours or their local landscape. Modellers can draw on a range of sources, from national statistics to information provided by small, ethnographic studies to explore the underlying mechanisms. While they can draw on standard economic theories, they can also use other theories such as those based on behavioural economics. The computer model can then be used to generate possible future scenarios and to study the effects of economic policies. ABM enables the testing of the validity of assumptions gleaned from different sources to see whether or not they generate the observed patterns.

Agent-based models can range from simple, abstract models to very complicated real-world case studies. They may have just two agents or millions of agents. And within a model, agents can represent different kinds of entities: people, households, firms, governments or countries or even animals.

Agents' characteristics fall under four possible headings:

- Perception: agents can see other agents in their neighbourhood and their environment.

- Performance: agents can act, such as moving and communicating.

- Memory: agents can recall their past states and actions.
- Policy: agents can have rules that determine what they do next.

Chapter 2 provides an introduction to doing ABM. For more background, see Gilbert and Troitzsch (2005) and Gilbert (2007).

1.4 The three themes of this book

Howitt (2012) suggested that agent-based economic models are 'the polar opposite to that of DSGE'. DSGE models in effect assume that 'people have an incredibly sophisticated ability to solve a computationally challenging intertemporal planning problem in an incredibly simple environment', while agent-based models assume that 'people have very simple rules of behavior for coping with an environment that is too complex for anyone fully to understand'. In short, Howitt argued that agent-based economic models can portray an economic system in which orderly behaviour can emerge as a result of interaction between heterogeneous agents, none of whom has any understanding of how the overall system functions.

In agent-based models, agents follow rules and react and interact over time. They may well be optimising, but it is within their perceived constraints, and they may not have full information. In contrast, neoclassical economics assumes people can optimise using full information (see, e.g. Axtell, 2007). In particular, in agent-based models, agents cannot foresee the future because it is determined by stochastic processes. And they may correct their behaviour following a mistake or not, depending on the learning algorithm used. DSGE models assume mistakes are not repeated.

The book focuses on using agent-based models to provide:

- The possibility of modelling heterogeneity
- An easy way to address dynamics
- The opportunity to model interactions between people and between people and their environment

We now take a brief look at each of these.

Heterogeneity

Traditional approaches to economics have long been criticised for 'lumping' things together. Think, for example, of a Cobb–Douglas production function in which two variables, labour and capital, are combined to produce output. Clearly, there are different types of labour and different types of capital, and one kind cannot replace another overnight: a bricklayer cannot just become a software designer, nor vice versa, and a factory producing cars cannot produce computer chips. Nor are all consumers the same: a rich household will have a very different spending pattern to a poor household. Some must save so that others can borrow. Indeed, without heterogeneity, there would be no scope for trading. ABM allows for such heterogeneity to be represented explicitly and without causing insuperable complications.

Dynamics

By dynamics, we here refer to adaptive processes, which, according to Leijonhufvud (2006), is the sense in which it was originally used in economics. Most economic textbooks only use comparative statics, that is, compare equilibrium situations. Yet as long ago as 1941, Samuelson pointed out that comparative statics were inadequate for the analysis of a range of economic problems (Samuelson, 1941). But as the examination of any basic economics textbook will show, comparative statics still dominates teaching. The question of how the economy moves from one equilibrium to another is not addressed. This is only now starting to change under the auspices of CORE, which gives prominence to dynamics (CORE, 2014). However, modelling dynamics by traditional methods is difficult as the mathematics quickly become unmanageable. Using ABM, simple rules can be applied and tested through simulation.

Interactions

People influence each other's behaviour. Herd behaviour is common in economics; people copy fashion, and markets take flight. Indeed, markets are based on interactions: sellers and buyers trade. The traditional economic models do not allow for this kind of interaction, but it is easily modelled using agents. ABM can also model in a simple manner how people can interact with the environment, for example, using up scarce resources.

1.5 Details of chapters

It is clearly impossible to cover everything presented in standard economics textbooks, which typically run to hundreds of pages (e.g. the British Begg *et al.*'s *Economics* (2011) and, from the United States, Varian's *Intermediate Economics* (2010)). So we have chosen topics within areas that seem to be particularly suitable for ABM, that is, where heterogeneity, interaction and dynamics are important.

Markets are a key theme of this book. We start with consumer choice in Chapter 3 and include fashion dynamics in Chapter 4 before introducing markets, through barter, in Chapter 5 with a fuller development in Chapter 6. The later chapters cover markets in the contexts of labour in Chapter 7 and international trade in Chapter 8. We have deliberately avoided discussion of financial markets as the usefulness of ABM has already been well established in this area by LeBaron (2006) and others. But Chapter 9 demonstrates the potentially explosive dynamics of the fractional reserve banking system. Chapter 10 shows how ABM can be used to model not only the interaction between economic agents but the interaction between agents and their natural environment.

Chapter 2: Starting agent-based modelling

Chapter 2 shows how to create a simple agent-based model and introduces the programming environment, NetLogo, that will be used for the models described in the rest of the book. The model simulates consumers shopping for fruit and vegetables in a produce market. The consumer agents are initially programmed to choose a market stall to purchase from at random, and then successive enhancements are made to record the cost of purchases, to stop them revisiting a stall they have previously been to and to try to find the cheapest stalls to buy from. Many of the basic building blocks of NetLogo programming are described.

Chapter 3: Heterogeneous demand

Chapter 3 introduces ABM by showing how it can be used to create heterogeneous agents whose characteristics and behaviour can be summed to generate observed macro patterns. Three models are presented in which agents represent households. The first model generates a budget distribution to replicate the observed distribution of income in the United Kingdom. The second adds a

Cobb–Douglas utility function to draw both individual and aggregate demand curves and demonstrates how consumers' choices can be tracked from their preferences to their contribution to aggregate demand. The third model provides a practical way of examining the effect on demand of price changes. Finally, the chapter compares the results from these simple models using heterogeneous agents with those from a 'representative agent' analysis.

Chapter 4: Social demand

Chapter 4 adds interaction between agents and dynamics. Consumers' behaviour is now not just influenced by prices and incomes but also by what others do, especially family and friends. ABM is well suited to modelling such social networks, and the first model in this chapter does this very simply using the concept of social circles. Next, we introduce threshold models and show how these can be combined with the social network model to examine possible adoption patterns of new products. The chapter then reviews the adoption of new technology by households in the United Kingdom and finally presents a case study of the adoption of fixed-line phones in the United Kingdom from 1951 to 2001.

Chapter 5: Benefits of barter

Chapter 5 demonstrates how ABM allows us to explore the dynamics of heterogeneous agents interacting by trading. Using the two-good economy much beloved of economics textbooks, agents trade by barter. We model an exchange economy broadly based on a description of trading that occurred in a prisoner-of-war camp. We start by creating a model that reproduces the Edgeworth Box to tease out the essentials of the barter process between two individuals. We explore the effectiveness of different price setting mechanisms in clearing the market and achieving Pareto optimality, starting with the theoretical Walrasian auctioneer. Then we extend this model to allow 200 agents to trade. We show that a simple stochastic peer-to-peer trading mechanism can produce a large increase in welfare, even if total utility is not maximised.

Chapter 6: The market

Chapter 6 focuses on the decisions of firms and demonstrates how ABM can easily accommodate the dynamic and interactive nature of markets. We present three models. The first is based on Cournot's classic model of duopoly and its Nash equilibrium but introduces the possibility of inaccurate information. The second model is based on small shops in the real world that do not have the benefit of the perfect foresight that is granted to firms operating under perfect competition and illustrates the dynamics of survival. The final model reflects business in the digital world, where there is no limit on capacity.

Chapter 7: Labour market

Heterogeneity and dynamics are the central themes of Chapter 7. The United Kingdom labour market is characterised by large flows and great diversity among the participants. The chapter starts with a model to generate the distribution of wages. It then adds the interaction between employers and workers as employers try to fill vacancies and workers seek jobs, touching briefly on the very skew distribution of firms by size. Finally, the various flows of workers between employers and into and out of the labour force are added to produce a simple, but interesting, model of the labour market of a small town. It also shows how micro and macro aspects can be combined in one model.

Chapter 8: International trade

Chapter 8 presents a simple model of trade between one country and the rest of the world, focusing on the determination of exchange rates. Five countries are used as examples, two with floating exchange rates and three in the Eurozone. Four scenarios are examined: inflation, depreciation, exogenous change in demand for exports and the impact of fiscal policy changes. The model focuses on dynamics. Even this simple model serves to highlight the difficulty of modelling the dynamics of international trade. It also shows clearly the constraints under which Eurozone countries operate.

Chapter 9: Banking

Chapter 9 uses a simple agent-based model to explore the basic features of fractional reserve banking and shows how the reserve and capital adequacy ratios imposed by regulators can dampen an otherwise explosive system. It illustrates how ABM can accommodate heterogeneity in that both savers and borrowers can be represented; how micro and macro aspects can be combined in one model, unlike the conventional textbook treatment of banking; and the importance of taking dynamic processes fully into account in modelling the banking system.

Chapter 10: Tragedy of the commons

Chapter 10 demonstrates how ABM can handle the interaction of agents with their environment as well as with one another by addressing the problem of the overuse of shared resources. In the 'tragedy of the commons', the pursuit of self-interest results in overuse of a common pool resource to the detriment of all. A model, inspired by English common land, is built in two stages. First, a meadow is created and its carrying capacity established. Then commoners are introduced. If there are no restrictions on the number of cows grazed on the meadow, there is overgrazing and 'the tragedy' ensues. But by following actual practice observed in England and Switzerland of setting limits on the number each commoner is allowed to graze, the model demonstrates that the tragedy can be avoided. The model can be readily adapted to accommodate other scenarios.

Chapter 11: Summary and conclusions

The final chapter summarises the models to show how ABM has addressed the weaknesses in the existing methods identified in Section 1.2 by allowing heterogeneity, facilitating dynamics and modelling interactions between people and their environments and thereby improving the link between micro- and macroeconomics. It also sets out some of the problems that need to be addressed in order for ABM's potential to make a useful contribution to economics to be fully realised.

The models

We present 19 models in Chapters 3–10, ranging from modules to be used in larger models to a real-world model. In each case, we follow Müller *et al.* (2014) who suggested 'a structured natural language description plus the provision of source code' as being 'particularly suited for academic purposes'. We describe the models in natural language in the chapters. The appendices to the chapters provide more details based on the ODD (Overview, Design concepts, and Details) protocol (Grimm *et al.*, 2010) and include pseudocode. The code itself is provided on the website http://cress.soc.surrey.ac.uk/.

References

Arthur, W.B. (1999) Complexity and the economy. *Science*, 284 pp.107–109.

Arthur, W.B. (2014) *Complexity and the Economy*. Oxford: Oxford University Press.

Axtell, R.L. (2007) What economic agents do: How cognition and interaction lead to emergence and complexity. *Review of Austrian Economics*, 20, pp.105–122.

Begg, D., Vernasca, G., Fischer, S. & Dornbusch, R. (2011) *Economics*. Tenth Edition. London: McGraw-Hill Higher Education.

Colander, D. (2006) *Post Walrasian Macroeconomics: Beyond the Dynamic Stochastic General Equilibrium Model*. Cambridge: Cambridge University Press.

CORE (2014) *The CORE project* [Online]. Available at: http://core-econ.org/ [Accessed 31 January 2015].

Economist (2010) *Agents of change: Conventional economic models failed to foresee the financial crisis*. Could agent-based modelling do better? 22nd July [Online]. Available at: http://www.economist.com/node/16636121 [Accessed 31 January 2015].

Economist (2013) *Keynes's new heirs: Britain leads a global push to rethink the way economics is taught* [Online]. Available at: http://www.economist.com/news/britain/21590555-britain-leads-global-push-rethink-way-economics-taught-keyness-new-heirs [Accessed 31 January 2015].

Epstein, J.M. (2006) *Generative Social Science*. Princeton: Princeton University Press.

Epstein, J. M. & Axtell, R. (1996) *Growing Artificial Societies. Social Science from the Bottom Up*. Cambridge, MA: The MIT Press.

Farmer, J.D. & Foley, D. (2009) The economy needs agent-based modelling. *Nature*, 460, pp.685–686.

Gilbert, N. (2007) *Agent-based Models*. London: Sage.

Gilbert, N. & Troitzsch, K. (2005) *Simulation for the Social Scientist*. Oxford: Oxford University Press.

Grimm, V., Berger, U., DeAngelis, D.L., Polhill, J.G., Giske, J., & Railsback, S.F. (2010) The ODD protocol: A review and first update. *Ecological Modelling*, 221, pp.2760–2768.

Hayek, F. (1931) *Prices and Production*. London: George Routledge & Sons Ltd.

Howitt, P. (2012) What have central bankers learned from modern macroeconomic theory? *Journal of Macroeconomics*, 34, pp.11–22.

Jevons, W.S. (1888) *The Theory of Political Economy*. Third Edition. London: Macmillan & Co. [Online]. Available at: http://www.econlib.org/library/YPDBooks/Jevons/jvnPECover.html [Accessed 31 January 2015].

Keynes, J.M. (1936/1970) *General Theory of Employment, Interest and Money*. London: Macmillan.

Kirman, A.P. (1992) Whom or what does the representative individual represent? *Journal of Economic Perspectives*, 6(2), pp.117–136.

LeBaron, B. (2006) Agent-Based Computational Finance. In Tesfatsion, L. & Judd, K.L., eds, *Handbook of Computational Economics*. Elsevier: Amsterdam, pp.1187–1233.

Leijonhufvud, A. (2006) Episodes in a Century of Macroeconomics. In Collander, D., ed, *Post Walrasian Macroeconomics*. Cambridge: Cambridge University Press, pp.27–45.

Lucas, R. (1976). Econometric Policy Evaluation: A Critique. In Brunner, K. & Meltzer, A., eds, *The Phillips Curve and Labor Markets*. Carnegie-Rochester Conference Series on Public Policy, 1. Amsterdam: North Holland, pp.19–46.

Markose, S. (2014) *Report on ESRC Conference on diversity in macroeconomics new perspectives from agent-based computational, complexity and behavioural economics:* 24–25 February 2014 [Online]. Available at: http://essex.ac.uk/economics/documents/conference-report.pdf. For papers and slides: http://www.acefinmod.com/esrc2014.html [Accessed 31 January 2015].

Marshall, A. (1920/1961) *Principles of economics*. London: Macmillan.

Morgan, M.S. (2012) *The World in the Model*. Cambridge: Cambridge University Press.

Müller, B., Balbi, S., Buchmann C.M., de Sousa, L., Dressler, G., Groeneveld, J., Klassert, C.J., Le, Q.B., Millington, J.D.A., Nolzen, H., Parker, D.C., Polhill, J.G., Schlüter, M., Schulze, J., Schwarz, N., Sun, Z., Taillandier, P., Weise, H. (2014) Standardised and transparent model descriptions for agent-based models: Current status and prospects. *Environmental Modelling & Software*, 55, pp.156–163.

Petty, W. (1690) *Political arithmetick*. Robert Clavel at the Peacock, and Hen, Mortlock at the Phoenix in St. Paul's Church-yard [Online]. Available at: http://socserv2.socsci.mcmaster.ca/~econ/ugcm/3ll3/petty/poliarith.html [Accessed 31 January 2015].

Ramsey, F.P. (1927) A contribution to the theory of taxation. *Economic Journal*, 37, pp.47–61.

Ramsey, F.P. (1928) A mathematical theory of saving. *Economic Journal*, 37, pp.543–559.

Royal Economic Society (2014) *New teaching for economics: The INET-CORE project* [Online]. Available at: http://www.res.org.uk/view/art3Jul14Features.html [Accessed 31 January 2015].

Samuelson, P. (1941) The stability of equilibrium: Comparative statics and dynamics. *Econometrica*, 9(2), pp.97–120.

Samuelson, P. (1948) *Economics*. New York: McGraw Hill.

Smith, A. (1776/1861) *Wealth of Nations*. Edinburgh: Adam Charles & Black.

Squazzoni, F. (2010) The impact of agent-based models in the social sciences after 15 years of incursions. *History of Economic Ideas*, xviii, pp.197–233.

Stiglitz, J.E. & Gallegati, M. (2011) Heterogeneous interacting agent models for understanding Monetary economies. *Eastern Economic Journal*, 37(1), pp.6–12.

Stockton, D. (2012) *The review of the Monetary Policy Committee's forecasting capability*. Presented to the Court of the Bank of England [Online]. Available at http://www.bankofengland.co.uk/publications/Documents/news/2012/cr3stockton.pdf [Accessed 31 January 2015].

Trichet, J-C. (2010) *Reflections on the nature of monetary policy non-standard measures and finance theory*. Speech by President of the ECB, Opening address at the ECB Central Banking Conference Frankfurt, 18 November 2010. Available at https://www.ecb.europa.eu/press/key/date/2010/html/sp101118.en.html [Accessed 24 May 2015].

Varian, H. (2010) *Intermediate Microeconomics*. Princeton: Princeton University Press.

Wickens, M. (2008) *Macroeconomic Theory: A Dynamic General Equilibrium Approach*. Princeton: Princeton University Press.

2

Starting agent-based modelling

2.1 Introduction

While it is possible just to use an agent-based model that someone else has developed, it is much better and more interesting to see what goes on 'under the hood', so that you can see and understand the program code that is making the model work. Learning how to program, as well as being a worthwhile exercise in its own right, will allow you to modify existing programs, for example, to explore the effect of different settings and different assumptions, and eventually to build your own programs. Programming used to be a matter for experts, requiring many months of study or a degree in computer science. Fortunately, advances in programming languages and interfaces have meant that programming is becoming ever more easily accessible to those without expert knowledge. In this book, we use a programming system called NetLogo (Wilensky, 1999) that was originally designed for secondary (high) school pupils and is still used, particularly in the United States, to teach science by means of simulations. The origins of NetLogo mean that a great deal of attention has been paid to making the NetLogo system easy to use and to understand. We will take advantage of that in this book, and we will also benefit from the fact that NetLogo is especially good for developing agent-based models. The authors describe it as a 'multi-agent programmable modelling environment'.

NetLogo has three parts:

- A code editor to write programs
- An interface that shows the controls to operate the program and any of a range of graphs, maps and other outputs to show what the program is doing
- A documentation editor that can be used to describe the program and what it is intended to do

Agent-Based Modelling in Economics, First Edition. Lynne Hamill and Nigel Gilbert.

Each of these is independent so, for example, you run a program that someone else has written and observe what it is doing without looking at the code. NetLogo comes with a large library of pre-built sample models taken from physics, chemistry, geography and other disciplines, as well as economics, and trying these is a good way of starting to become familiar with it.

NetLogo can be downloaded from http://ccl.northwestern.edu/netlogo/. It is open source and free and works almost identically on Windows, Mac OS and Unix systems. You might like to download it onto your computer now and follow along as you work through this chapter. There are other agent-based modelling environments (examples are Mason and RePast, both of which are open source but are based on the programming language, Java, so that using them needs some prior knowledge of that language, and AnyLogic, a commercial system), but for beginners, NetLogo is at the moment the best place to start.

This chapter explains some aspects of NetLogo, but for a fuller account, see the textbook authored by its main developer (Wilensky & Rand, 2015). Other books on agent-based modelling also include introductions, for example, Railsback and Grimm (2011) and Gilbert (2007). The NetLogo system itself includes an excellent tutorial and many code examples in its model library. There is also a NetLogo Users Group email list at https://groups.yahoo.com/neo/groups/netlogo-users/info and a StackOverflow community at http://stackoverflow.com/questions/tagged/netlogo where questions can be asked.

To illustrate how NetLogo is used, we will develop a simple model and explain the program code step by step. First, let us see the model in action (the code can be downloaded from the website: *Chapter 2*).

2.2 A simple market: the basic model

Much of this book is about modelling markets of different types. One of the simplest is a produce market, such as is often found in towns and cities selling fruits and vegetables. In this model, there are shoppers, each with a shopping list, and a number of market stalls, each selling a range of fruits and vegetables. The shoppers want to buy the items on their lists, which will differ from one shopper to the next, and may want to minimise the cost of their shopping. The stallholders sell their produce for different prices, depending on what they think the customers will pay, the prices that they paid in a wholesale market and other factors. Not all stalls sell the complete range of fruits and vegetables.

Agent-based models almost always follow a standard pattern: they are initialised with parameters that define the starting situation. Then the model is executed to simulate the passage of time. At each step, representing some short duration (e.g. a day), each agent performs some action (or does nothing), as determined by its behavioural rules. The action can include communicating with other agents, changing the environment, moving through the environment and many other things. The execution of the program continues, step by step, until either some programmed stopping condition is met or the user stops the simulation manually. While the program runs, what is happening to the agents can be measured on graphs or monitors. This will become clearer as we work through the example model.

Figure 2.1 shows the interface of the model at a point midway through the simulation. The houses represent the market stalls, and the people are the shoppers. To run the model, you first press the `setup` button at the top left, which initialises the model, and then the `go` button to run it. The top slider is used to adjust the number of shoppers before the simulation begins. The slider under it, labelled `walking speed`, adjusts the speed at which the shoppers walk from stall to stall. This slider can be adjusted while the simulation runs to make the shoppers move faster or slower. The third slider sets the number of kinds of produce that traders keep on their stall. The three sliders allow the user to adjust the parameters of the model before and during each simulation run.

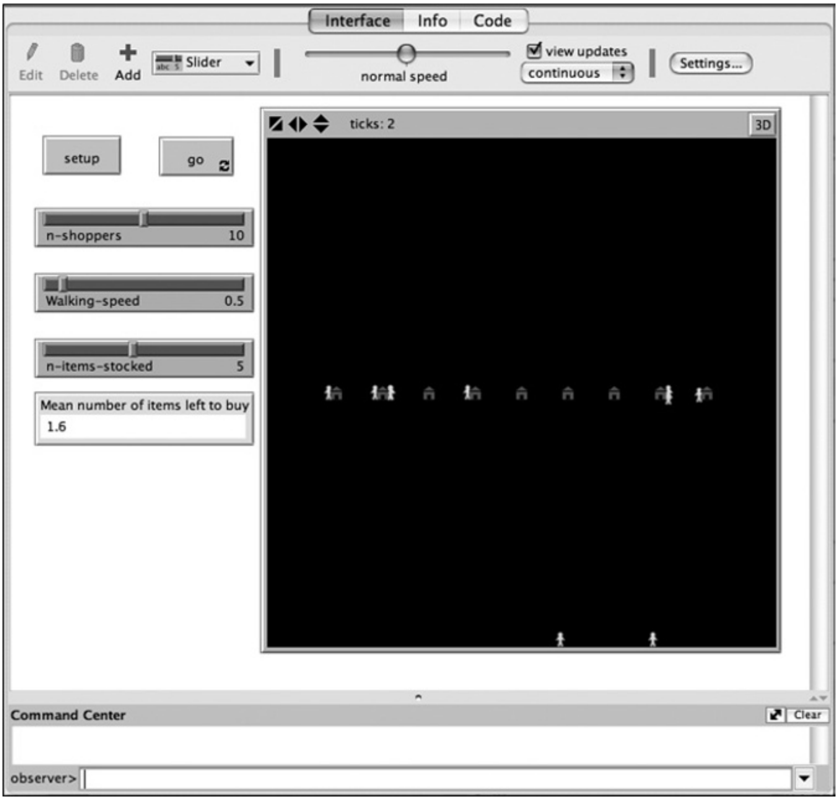


Figure 2.1 NetLogo interface window showing the market model after two ticks.

The bottom object is a monitor. It keeps a continually updated record of the average number of items on the shoppers' lists, that is, how many items have yet to be bought. Figure 2.1 shows the interface; clicking on the tab labelled 'Code' at the top takes you to the program itself (see Figure 2.2).

2.3 The basic framework

NetLogo programs have two sections: a 'setup' section which is executed once and which initialises the model to its starting state and a 'go' section which contains code that is executed again and again as the simulation runs. In addition, at the beginning, there is a header section that specifies the variables and the types of agents that will be used in the program.

The header for the example program (Box 2.1) begins by reserving two 'global' variables, `fruit-and-veg` and `mean-items` (line 1). The former will be used to hold a list of all the kinds of fruits and vegetables that any trader can offer for sale. The latter will in due course be used to hold the average number of items remaining on shoppers' shopping lists. When this variable has reached zero, everyone's shopping will have been completed. They are called global variables because they are accessible everywhere throughout the program.

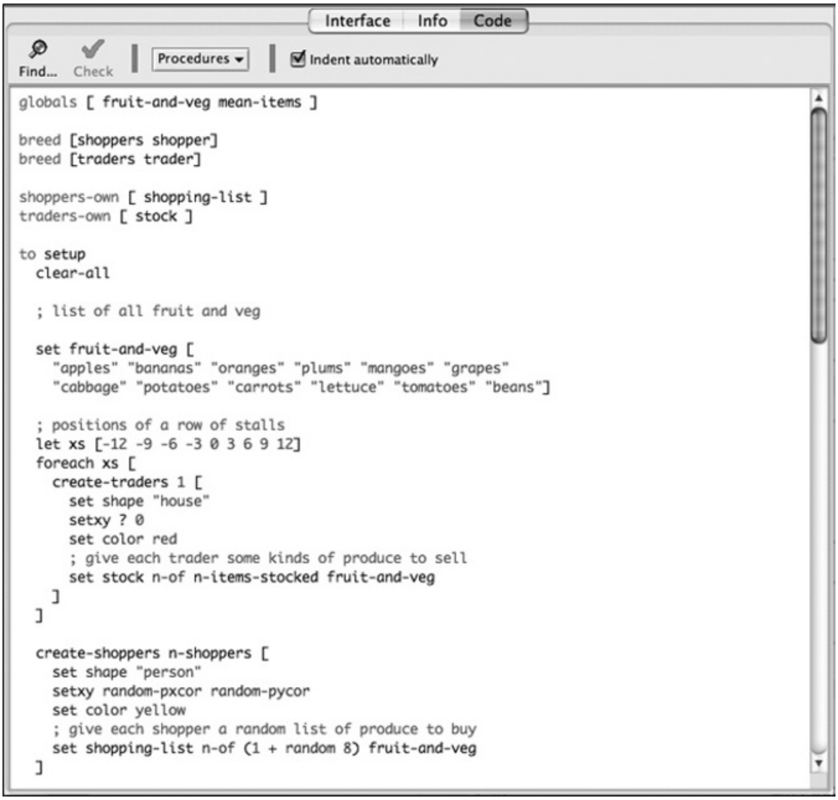


Figure 2.2 The NetLogo code window showing the top portion of the market model code.

Box 2.1 Market simulation header section.

```
globals [ fruit-and-veg mean-items ]
breed [shoppers shopper]
breed [traders trader]
shoppers-own [ shopping-list ]
traders-own [ stock ]
```

Note: the line numbers have been added; they are not part of the program code.

There are two kinds of agents in the model: shoppers and market traders. NetLogo allows you to name the types of agents as `breeds` (by analogy to the way that breeds of dog are different types of dog). One of the points emphasised in the previous chapter is that economic models need to allow for the fact that not everyone is the same, that is, to be able to deal with heterogeneity. In this simple market model, each shopper has a different list of items to buy, and each trader has different kinds of fruits and vegetables in stock. So each shopper has its own shopping list and each trader, its own list of what it sells. Shoppers are provided with a variable, `shopping-list`, that will be used to store that agent's own shopping list. Similarly, each trader has a variable, `stock`, in which will be stored a list of items that the trader has for sale.