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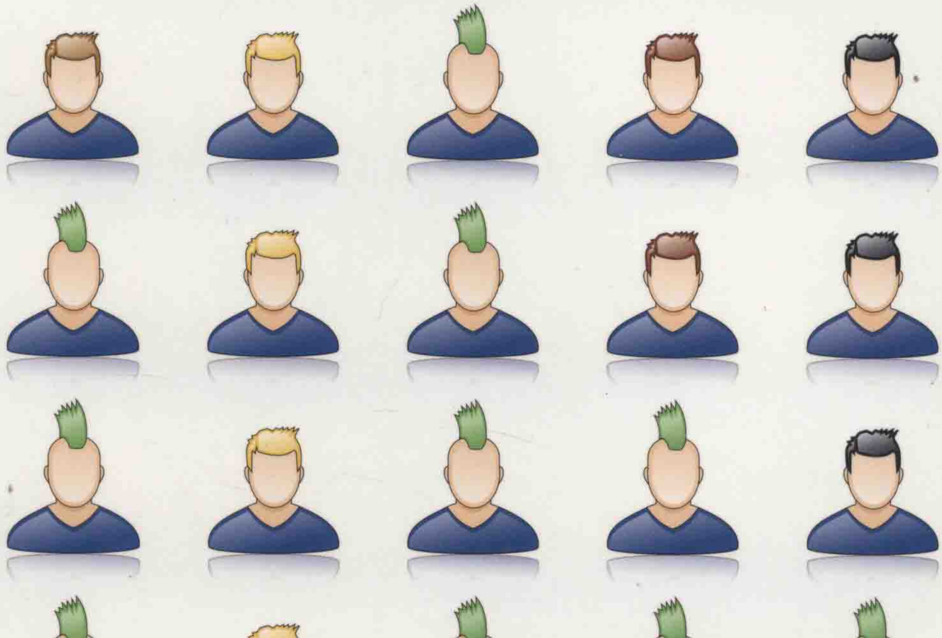

Simulating Innovation

Computer-based Tools for Rethinking Innovation

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Simulating Innovation

Preface

This book was written to help researchers in the fields of innovation studies, economics, organisation studies, sociology of science and policy modelling to become more familiar with a research approach that could complement their own. Those with no background in simulation modelling may see the advantages of working with social simulation modellers, or becoming a modeller themselves. Experienced modellers will find plenty of examples of social simulation, and especially of agent-based modelling to inspire their own work. The work here is inter-disciplinary, connecting with sociology, economics, business studies and operational research in particular, but may also interest researchers into complex adaptive systems more generally, who today may be found in such disciplines as physics, mathematics and biology.

In line with the various readerships there are multiple ways to read this book, depending on one's degree of interest in the areas of application, and on one's level of technical skill.

Researchers familiar with fields such as innovation studies or organisation studies may compare the ideas expressed here using simulation models with those from other sources, especially empirical studies. All the simulations discussed in the book use our own programs, some replications of models by other authors and some models of our own design. Readers can download programs from a website (http://www.simian.ac.uk/resources/models/simulating-innovation and see appendix), gain hands-on experience of using them, and explore the behaviours of these models beyond what is discussed in the text, perhaps leading to new findings. Those more experienced in computer programming, or wishing to become so, may want to examine the code, and may be able to suggest improvements or extensions.

The best test of simulation modelling is whether someone can replicate a model and its behaviour given just a written description of it. This task, it has long been recognised, is valuable but notoriously difficult (Axelrod, 1997a, Appendix; Axtell et al., 1996; Hales, Rouchier and Edmonds, 2003; Rouchier et al., 2008; Wilensky and Rand, 2007). Example attempts are both scarce in the literature and also mixed in their degree of success (Bigbee, Cioffi-Revilla and Luke, 2007; Edmonds and Hales, 2003; Macy and Sato, 2010; Rouchier, 2003). Even when plenty of technical details have been supplied, there is still scope for the unintentional omission of vital details. In addition, attempts to implement the same model in two different programming languages or with different hardware or operating systems can occasionally generate unexpected variation in program behaviour. The threat of such problems can be reduced if attempts are made to replicate as many as possible of other authors' models. Model replication attempts are also a good way to test one's understanding of the original descriptions of the models, and in this respect the collection of programs on our website may serve as a contribution to the field.

We encourage others to have a go at replicating our models. The more successful replications are reported, the more confidence people will have in social simulation as a research tool. Hence we outline our programs' workings, aiming at supplying enough detail to give modellers some idea of their core mechanisms, without overloading the text with technical details. The World Wide Web means that our programs can easily be made publicly available to those wishing to read them.

Given the space restrictions on this book, we have chosen to focus on simulation modelling. To have attempted to review the innovation literature would either have extended the book considerably or have risked being too brief to give a fair account. Fortunately, the areas we address with our models are mostly well served for books and journals. The classic by Rogers (2003), and recent collections edited by Malerba and Brusoni (2007) and Fagerberg, Mowery and Nelson (2005) are good starting points.

As well as declining to review the literature in innovation studies, we also omit giving a basic introduction to social simulation. This has been done elsewhere (Gilbert, 2008; Gilbert and Troitzsch, 2005). There are also software packages and training materials on the Internet. Some of the programs were written using *Microsoft Excel 2003/XP with VBA*, and versions of this software are widely used in companies and universities, although problems may be encountered with other versions of Excel and with spreadsheet programs that attempt compatibility with Excel. Most of the programs, however, were written for the agent-based modelling language, *NetLogo 5.0* (Wilensky, 1999). This is free to download (http://ccl.northwestern.edu/netlogo/) and install on Windows, Macintosh or Linux platforms. We find it easy to use and relatively easy to learn to program in, it having been developed from a programming language, *Logo*, that was originally intended for use by American primary school children. One of us (NG) has employed NetLogo for research, consultancy and teaching purposes for several years, and we have no hesitation in using it here. Programmers proficient in other languages should have few problems in transferring to it, though they might prefer to try to replicate the models in their favourite language, using our NetLogo code as a guide.

One of us (CW) was introduced to agent-based modelling and the study of complex systems through reading Robert Axelrod's book *The Complexity of Cooperation* (1997a) and Stuart Kauffman's *At Home in the Universe* (1996), before attempting to reproduce the models and computer experiments described therein using what was then a fairly rudimentary knowledge of Excel and VBA. Agent-based models can be more sophisticated today, and there are now plenty of academic departments around the world specialising in complexity research, but all of the programs described in this book can be run on home PCs and we hope the subject remains one an amateur or a visitor from another field can get into. We dare not hope to have attained the heights of these two books, or go on to have the same influence, but if the next generation of modellers and complexity scientists feels inspired to apply simulation modelling when investigating issues of innovation, we shall feel this book was worthwhile.

Acknowledgements

This book is based on work conducted as one part of the *SIMIAN* project at the University of Surrey, England. The project was funded by the National Centre for Research Methods, part of the UK's Economic and Social Research Council (ESRC). Thanks must go to Edmund Chattoe-Brown, University of Leicester, who co-authored the original funding bid, and to our colleagues in the Centre for Research in Social Simulation (CRESS) at Surrey University for contributing to a rich research environment during the project. In particular, Richa Sabharwal created the *SIMIAN* website, Lu Yang provided smooth administration of the project and its events, and Lynne Hamill, Ozge Dilaver-Kalkan and Jen Badham offered fruitful conversations on the topics of this book. CW would like to thank his former colleagues at Warwick Business School, where his PhD supervisor Stewart Robinson gave him both training in the art of simulation modelling, and also enough flexibility over time to be able to pursue wider interests, some of which prepared the way for the work for this book. CW also benefitted from attending the 2009 *Tenth Trento Summer School* at the University of Trento, Italy, the 2009 *Modelling Science* workshop at the Virtual Knowledge Studio, University of Amsterdam and the 2011 *SKIN* workshop at the University of Koblenz-Landau, Germany. We thank the organisers of these events for their invitations. We also thank CW's wife, Annelise, for the motivation provided by threatening not to marry him if the book's first draft was unfinished, and for relenting when he just fell short.

Material for this book was presented at various conferences, in particular the *European Association for the Study of Science and Technology* (EASST) 2010 conference, the *Dynamics of Institutions and Markets in Europe* (DIME) Final Conference in 2011 and the *European Conference on Complex Systems* (ECCS) in 2011, and we thank the audiences on those occasions for their comments. One of the models developed for Chapter 5 has already been described in a paper in the journal *Scientometrics* (Watts and Gilbert, 2011). Chapter 6 is a slightly modified form of a paper to the DIME Final Conference. Various models by other authors have been reproduced and discussed in this book, and the references to the original sources for these are contained in the text. As we are only too aware, innovative research involves re-combinations and re-interpretations of pre-existing parts. We hope we have done justice to these various sources of assistance, and any errors should, of course, be attributed first to us.

Contents

1. Why simulate innovation?

This book seeks to innovate in the tools we use for thinking about innovation. Computer simulation models can clarify our thoughts and explore their implications. Over the last two decades there have appeared descriptions of computer simulation models that address some of the issues surrounding innovative ideas, practices and technology, including how innovations can be generated, how they diffuse among people and organizations, and the impact innovations have on people's and organizations' other ideas, practices and technologies. This book will provide a critical survey of some of these tools for thinking, while also introducing a few tools of our own.

In this chapter we explain why one might want to be thinking about innovation, how it involves complex adaptive systems and how these can be studied, and hence why one might want to add computer simulation models to the tools one uses for innovation studies. The chapter concludes with an outline of the rest of the book.

WHY STUDY INNOVATION TODAY?

The Trouble with Financial Innovation

Innovation is currently held responsible for a lot. During the work for this book (2009–12) countries around the world have been suffering the after-effects of a wave of innovation in the financial world. The tale, as told by *Financial Times* journalist and trained social anthropologist Gillian Tett (2009), tells of brilliant minds being hired by investment banks and, full of excitement for their work, putting in long hours to generate innovative ways of making money (see also MacKenzie, 2009, 2011a). They began with the idea of extending the centuries-old concept of derivatives, a form of insurance, to a new application, that of insuring against the risk of a borrower defaulting on their debts. The tale is woven around a diverse collection of novel financial concepts and products, each requiring a new name or phrase: from CDS to CDO, CDO of ABS, mortgage-backed CDO, slice-and-dice, tranches, CDO-squared, Gaussian copula, sub-prime, super-senior, SIV and ABCP. Each one represented a new combination of pre-existing components or a new application for an existing idea. Once invented, the innovations were offered to new markets, scaled up to new levels, and sold off in unprecedented quantities to a variety of customers. These customers included not only traditional, but also some new financial players, most of whom had little knowledge about how these financial products worked. Understanding of the risks and value behind these novel products was also scarce among their producers, their owners, government regulators and insurers, but few saw any incentive for asking questions. When the underlying assets, mostly mortgages on houses, began to lose their market value, a house of cards was set to tumble, freezing markets and taking down banks and brokerages, insurers, investment and hedge funds, government finances and even governments themselves, and finally reduced the power of several nations. All this followed a frenzy of innovation.

At the same time, innovation is at the heart of proposed solutions to the crisis. Governments should introduce new regulations for the banking sector. R&D spending should be increased in other industries, especially manufacturing, in order to generate new growth to compensate for the losses. The gap between universities and businesses must be narrowed, with exchanges of knowledge between them, and more patents generated and spin-off companies set up based on academic research. Geographic clusters of firms must be seeded and protected, where interactions between the firms will generate the next big ideas in technologies. So innovation has been hero, then villain, and is now our best hope for salvation. It seems an apt moment to be writing about innovation.

The Trouble with Economics

Given the economic causes and effects of innovations such as those in the financial world, it might be thought that the topic of innovation would best be studied by economists. The primary focus of mainstream economics is efficient resource allocation, for which mathematical models have been developed based on the idea of a system in equilibrium. Solow (1956) provided a mathematical treatment to add resource growth to modelling as part of a dynamical equilibrium theory, but these models assume both population growth and technological change are givens, exogenous to the model. By this light, technological innovation is just an unexplained leftover when one has subtracted other factors behind resource stocks. Endogenous growth theory (e.g. Romer, 1986, 1990) considers some of the factors thought to be behind technological change, chiefly those that increase human capital, knowledge and innovation, such as R&D

spending, the level of government regulation and a culture of openness to change. A key difference from previous economic theories is the idea that investing in R&D can produce *increasing returns* to scale: acquired knowledge enables improvements in future knowledge production.

These attempts to study innovation endorse most of the common assumptions of mainstream economics, such as rational agents forming systems at equilibrium, and largely consist in developing equation-based models that will reproduce statistical patterns observed in data, in this case, data by country on GDP and growth, population size and R&D spending, among other measures. In so far as correlations are found between these variables, how the correlations come to be there is poorly understood. Representing the generating mechanisms means representing human behaviour, including representing its diversity, mathematically in such a way that it can be aggregated easily.

While mainstream economics remains attached to its assumptions and mathematical techniques, it continues to treat the topic of innovation poorly. This can be seen by the continued neglect in mainstream economics textbooks of fields that deal primarily with innovation: evolutionary economics and behavioural economics.

The pioneer of *evolutionary economics*, Joseph Schumpeter (1939, 1943), writing in the middle of the twentieth century, identified innovations and the entrepreneurs who develop innovative ideas into marketable products as vital to economic growth (Heilbroner, 2000, Chapter 10). The theories of neoclassical economics focus on markets at equilibrium. But according to these theories, at the equilibrium point, competition between firms has reduced profit to zero. In this case, why remain in the market? This seeming puzzle could be solved, according to Schumpeter, by reference to innovation. When companies bring new products to market, or develop improved methods of production resulting in lower costs, they enjoy an advantage over their competitors and may charge prices that include a premium, thus yielding non-zero profits. Their new offerings may also enhance the value of other goods and services, and undermine the market appeal of yet others, a process Schumpeter dubbed 'creative destruction' (Schumpeter, 1943, p. 83). The advantage is only temporary, however, since competitors may imitate the innovator. For this reason, some of the innovator's profit should be invested in the R&D that could generate future innovations and maintain some competitive advantage. Alongside efficient allocation of resources, forcing firms to innovate is the second major justification for markets. But uncertainty exists about how much to invest in this R&D, how best to go about seeking innovations, how much one innovation depends on knowledge of another and how long it will take to generate the next one. Different companies may adopt different strategies for this, with some investing heavily in R&D and others hoping to be able to imitate quickly and cheaply when the investments by others have generated results. At some times there may be a flurry of new products, at other times the diffusion of recently introduced products, and at yet other times there may be a period of relative quiet, perhaps resembling a market equilibrium state. Thus, while undergraduate economics courses teach students to focus on the ideas of equilibrium being reached by a market of identical competing firms, the vision developed from Schumpeter's work is that of *heterogeneous* (diverse) firms in a *dynamic* market.

Another field trying to attract more attention within economics is *behavioural economics*. When reasoning about the decisions made by suppliers and customers, neoclassical economics assumes that decision makers know all the available options, the probabilities and monetary values of all consequences of these options, and will choose between the options so as to maximise their expected monetary gain. This view of human decision makers as rational optimisers with perfect information, or *homo economicus*, was criticised by the political scientist, Herbert Simon, beginning in the 1940s and continuing in the decades since (Simon, 1948, 1955a, 1957, 1991). In its place, Simon and collaborators proposed that human decision makers had limited information on options, probabilities and values, and limited ability to process the information they had in a short enough time for it to be useful. Instead, of being infinitely capable rational optimisers, 'bounded rational' humans employed relatively quick and easy rules of thumb, called heuristics, to search for solutions that were, if not the best possible, usually sufficiently good for survival (Simon, 1955a; Simon and Newell, 1958). Nelson and Winter (1982) combined this view of bounded rational agency with evolutionary economics. Laboratory experiments by psychologists Kahneman, Slovic and Tversky (1982) confirmed that how human beings actually performed decision making resembled the use of heuristics more than it did mathematical optimisation. Both Simon and Kahneman have since been rewarded with Nobel Memorial Prizes in Economic Sciences (in 1978 and 2002, respectively). In the 1990s, support for research into actual economic behaviour continued to build (Akerlof and Shiller, 2009; Kahneman, 2011; Klein, 1998). More recently, interest has grown in the study of what it is that decision makers seek to improve, in particular, happiness (Frey, 2008; Layard, 2011), instead of money. Despite this, an informal survey of the undergraduate-level textbooks in the economics sections of bookshops and libraries reveals that most still lack chapters devoted to either evolutionary or behavioural economics.

Following the financial crisis, however, confidence in mainstream economics has been shaken (Blanchard, 2012; Frydman and Goldberg, 2011;

Keen, 2011; Turner, 2012). There is an opportunity for rethinking the subject's core material, that is, what is taught to students, and also what is funded, what research is published in the most widely read journals, who gets employed by the most prestigious academic institutions and who will go on to influence the next generation of society's leaders. Time and effort is being devoted to innovative approaches, be these either the invention of new methods, or the importing of ideas from other fields, including psychology, sociology, neuroscience, cognitive science, biology and the various fields which study complex adaptive systems.

New Sources on Innovation

The information age has brought new data sources to help the change in focus. There is more emphasis on attempts to count innovations. In technology there are data on patents, including who patents what, who they patent it with and which patents refer to which others (Fleming, Mingo and Chen, 2007; Fleming and Sorenson, 2001; Sorenson, Rivkin and Fleming, 2006; Trajtenberg, 1990). Similarly, data on academic publications, their co-authors and their citations, give insights into innovation production within universities and other research institutes (Boerner, Maru and Goldstone, 2004; Goldenberg et al., 2010; Price, 1965; Small, 1973). Electronic records of individuals' interactions, such as email communications, the Internet Movie Database (www.imdb.com) or geographical tracking devices can provide impressions of the social networks within which information about innovations flows and ideas are combined to generate new innovations.

In addition to these quantitative sources of data, qualitative sources, especially ethnographic studies over the last 30–40 years, have caused a revision of views of innovation generation and adoption. Seen close up, the supposed events of invention and adoption of new ideas, practices or products become more complex and less identifiable (Akrich, Callon and Latour, 2002; Akrich et al., 2002; Bijker, 1995; Bijker and Law, 1992). Since the 1990s, developments in artificial intelligence, robotics and cognitive science (Clark, 1997; Hutchins, 1995a, b) have promoted a view of the human decision maker as being *embedded*, *embodied* and *social*, with decisions dependent on a historical context, on interaction with a material environment and on collective effort.

It remains to be seen whether analyses of these quantitative and qualitative datasets will lead to better policies on innovation. Some uses of the datasets, such as policies that attempt to base continuance of funding on past production of patents or publications, could cause innovators to adapt their behaviour from that which helped generate the past data.

Unlike, say, astrophysicists, social scientists have the potential to disturb the systems they study. However, where policy and behaviour has yet to reflect the results of analyses, the datasets may help us to understand retrospectively how innovations were generated, how they interrelate, how they diffuse and what their impact may be.

Both quantitative and qualitative studies can inform the creation and revision of theories about innovation, which in turn can inform policy making. Theorising, however, can be hard to perform in unambiguous, coherent detail, with its implications spelled out. The time is ripe for a technique that allows theorising to capture some of the complex networks of interdependencies, and the dynamic behaviour that results. In recent decades a new type of tool has emerged for improving the rigour of theories and exploring their coherence and consequences, generating new hypotheses for empirical studies (Davis, Eisenhardt and Bingham, 2007). These are computer simulation models, and this book applies them to the study of innovation. In this we draw upon papers and books by others that have appeared over the last 20 or so years. These works apply simulation models to the diffusion of innovations through social networks, to collective learning in organisations, to the structure of academic science publications, to the adoption and adaptation of technologies in complex contexts and to technological evolution and the formation of innovation networks, to name the major topics of our chapters. Given that innovation remains as important an area as ever, and given the numbers of these tools, it seems a good time to highlight some of the models, including their features, assumptions and purposes, and identify some recommendations for future models.

WHAT IS MEANT BY 'INNOVATION'?

A Few Common Distinctions

There are many uses for the word 'innovation', and uses in this book will reflect several different bodies of literature, although the authors of models can be quite vague about the types of innovation they intend to apply them to. A few common distinctions may be made, however.

Two ideas seem essential to the concept of innovation. The more obvious idea is that it involves *newness*, or novelty. For example, there may be a new item or service brought to market (*product innovation*), or a new method for producing a product more cheaply than before (*process innovation*). The second idea is that the new thing will be of some value to someone, that is, it will be an improvement, reaching a new level of