Chapter 1
Introduction

1.1 Overview

As computer simulation has developed as a methodology, so its range of applications has grown across different fields. Beyond the use of mathematical models for physics and engineering, simulation is now used to investigate fields as varied and disparate as political science, psychology, evolutionary biology, and many other disciplines.

With simulation becoming such a common adjunct to conventional empirical research, debate regarding the methodological merits of computer simulation continues to develop. Some fields, artificial life being the primary example used in this text, have developed using computer simulation as a central driving force. In such a case, researchers have developed theoretical frameworks to delineate the function and purpose of computer simulation within their field of study.

However, the expansion of computer simulation into fields which use empirical study as a central methodology means that new frameworks for the appropriate use of simulation must develop. How might simulation enhance one's use of conventional empirical data? Can simulations provide additions to empirically-collected data-sets, or must simulation data be treated entirely differently? How does theoretical bias influence the results of a simulation, and how can such biases be investigated and accounted for?

The central goal of this text is to investigate these increasingly important concerns within the context of simulation for the social sciences. Agent-based models in particular have become a popular method for testing sociological hypotheses that are otherwise difficult or impossible to analyse empirically, and as such a methodological examination of social simulations becomes critical as social scientists begin to use such models to influence social policy. Without a clear understanding of the relationship between social simulation and social sciences as a whole, the use of models to explain social phenomena becomes difficult to justify.

E. Silverman, *Methodological Investigations in Agent-Based Modelling*,
Methodos Series 13, https://doi.org/10.1007/978-3-319-72408-9_1

Bearing in mind this central theme, this text will utilise a modelling example which will be revisited regularly in Parts I and II. This example will serve as a means for illustrating the important concepts described in the various modelling frameworks under discussion, and for tying together these frameworks by showing the effect of each upon the construction and implementation of a simulation. This central example takes the form of a model of bird migration; this example seemed most appropriate as this sort of problem can be examined through various modelling means, from mathematical to agent-based computational models. The context and purpose of this hypothetical model will vary from example to example, but the central concern of developing an understanding of the behaviour of migratory birds will remain throughout.

Toward the latter half of Part II, we will use the classic example of Schelling's residential segregation model (Schelling 1971) to discuss some particular methodological points in detail. Part III will delve deeply into specific examples of agent-based modelling work in the field of demography in order to illustrate how the modelling concepts discussed in Parts I and II can influence the practice of modelling in social science.

1.2 Artificial Life as Digital Biology

The field of artificial life provides a useful example of the development of theoretical frameworks to underwrite the use of simulation models in research. The Artificial Life conference bills itself as a gathering to discuss 'the simulation and synthesis of living systems'; with such potentially grandiose claims about the importance of artificial life simulations, theoretical debate within the field has been both frequent and fierce.

In the early days of Alife, Langton and other progenitors of this novel research movement viewed simulation as a means to develop actual digital instantiations of living systems. Beyond being an adjunct to biology, Alife was viewed as digital biology, most famously described as the investigation of 'life-as-it-could-be' (Langton 1992). Ray boasted of his Tierra simulation's explosion of varied digital organisms (Ray 1994), and theorists proposed this sort of digital biology as a means for divining the nature of living systems.

1.2.1 Artificial Life as Empirical Data-Point

Since these heady days Artificial life has sought more conventional forms of methodological justification, seeking to link simulation with more conventional means of data-gathering in biology. This has lead to varying forms of theoretical justification within Alife, ranging from further explorations of Langton's early ideas

(Bedau 1998; Silverman and Bullock 2004) to the use of Alife simulation as a form of 'opaque thought experiment' (Di Paolo et al. 2000).

Within this text, these varying theoretical frameworks for Alife will be examined in turn, both within the context of biology and within Alife itself. Once Alife seeks direct links with conventional biology, theoretical justification becomes correspondingly more difficult, and thus the debate must branch out into more in-depth discussions of biological modelling methodology. An investigation of the use of modelling in population biology, beginning with the somewhat-controversial ideas of Levins (1966, 1968) provides a means for describing and categorising the most important methodological elements of biological models. Having developed an understanding of the complex relationship between biology and Alife, we can then proceed to a discussion of the future of modelling within the social sciences.

1.3 Social Simulation and Sociological Relevance

Social simulation has appeared in the limelight within social science quite recently, starting with Schelling's well-known residential segregation model (Schelling 1978) and continuing into Axelrod's explorations of cooperative behaviour (Axelrod 1984). The development of simple algorithms and rules that can describe elements of social behaviour has led to an increasing drive to produce simulations of social systems, in the hopes that such systems can provide insight into the complexity of human society.

The current state-of-the-art within social simulation relies upon the use of agent-based models similar to those popularised in Alife. Cederman's influential book describing the use of such models in political science has helped to bolster an increasing community of modellers who hope that such individual-based simulations can reveal the emergence of higher-order complexity that we see around us in human society (Cederman 1997). Social science being a field where the empirical collection of data is already a significant difficulty, the prospect of using simulation to produce insights regarding the formation and evolution of human society is an enticing one for many.

1.3.1 Methodological Concerns in Social Simulation

Of course, with such possibilities comes great debate from within the social science community. Proponents offer varying justifications of the potential power of simulation in social science; Epstein echoes the Alife viewpoint by proposing that social simulation can provide 'generative social science,' a means to generate new empirical data-points (Epstein 1999). Similarly, Axelrod stresses the ability of social simulation to enhance conventional empirical studies (Axelrod and Tesfatsion 2006).

Others however are more cautious with their endorsement of social simulation. Kluver and Stoica stress the difficulty in creating models consistent with social theory (Klüver et al. 2003), noting that social systems do not lend themselves to the same hierarchical deconstruction as some other complex systems. Others theorise that social simulation faces the danger of incorporating vast theoretical biases into its models, eliminating one of the potential strengths of social models: a means for developing more general social theory (Silverman and Bryden 2007).

Further examinations of these questions within this text will seek to link such ideas with the methodological frameworks developed within Alife modelling and biology. While both fields display obvious differences in both methodological and theoretical objectives, the philosophical difficulties facing agent-based modelling in these contexts are much the same. In both cases the link between empirical data-gathering and simulated data-generation is difficult to develop, and as a consequence the use of simulation can be difficult to justify without a suitable theoretical justification.

1.4 Case Study: Schelling's Residential Segregation Model

Having developed a detailed comparison between the use of models in biology and social science, this text will use Schelling's residential segregation model as a case study for examining the implications of the theoretical frameworks discussed and outlined in that comparison. Schelling's model is famously simple, its initial version running on nothing more than a chequerboard, but its conclusions had a far-reaching impact on social theory at the time (Schelling 1978). Schelling's ideas regarding the 'micromotives' of individuals within a society, and the resulting effects upon that larger society, sparked extensive discussion of the role of individuals in collective social behaviour.

1.4.1 Implications of Schelling's Model

With this in mind, our investigation will explore the reasons for Schelling's great success with such a simple model, and its ramifications for future modelling endeavours. How did such an abstract formulation of the residential segregation phenomenon become so powerful? What theoretical importance did Schelling attribute to his model's construction, and how did that influence his interpretation of the results? Finally, how does his model illuminate both the strengths and weaknesses of social simulation used for the purpose of developing social theory? All of these questions bear upon our final examination of the most appropriate theoretical framework for social simulation as a whole.

1.5 Social Simulation in Application: The Case of Demography

Having developed some theoretical approaches to social simulation, we will need to move on to discuss the establishment of these methods as a trusted and functional element of the social scientist's toolbox. We will take on this problem by investigating the field of demography, the study of human population change. Demography is a fundamentally data-focused discipline, relying on at times vast amounts of complicated survey data to understand and predict the future development of populations (Silverman et al. 2011). We will investigate the core assumptions underlying demographic research, discuss and analyse the methodological shifts that have occurred in the field over the last 350 years (Courgeau et al. 2017), and develop a framework for a *model-based demography* that incorporates simulation as a central conceit.

1.5.1 Building Model-Based Demography

In order to understand the challenges facing a model-based social science, we will discuss several examples of agent-based approaches to demography. Starting with some inspirational work from the early 2000s (Billari and Prskawetz 2003; Axtell et al. 2002; Billari et al. 2007), we will move on to current work integrating statistical demographic modelling directly into an agent-based approach. We will examine the benefits and the shortcomings of these models, and in the process develop an understanding of the power of a scenario-based approach to the study of future population change. Finally, we will evaluate the progress of model-based demography thus far, and present some conclusions about the lessons we can take from this in our future research efforts.

1.6 General Summary

This text is organised as essentially a three-part argument. In Part I, the theoretical underpinnings of Alife are examined, and their relationship to similar modelling frameworks within population biology. Part II reviews the current state-of-the-art in simulation for the social sciences, with a view toward drawing comparisons with Alife methodology. A subsequent analysis of theoretical frameworks for social simulation as applied to a specific case study provides a means to draw these disparate ideas together, and develop insight into the fundamental philosophical and methodological concerns of simulation for the social sciences. Finally, in Part III we take the specific example of demographic research and attempt to build a cohesive

theoretical framework through which social simulation approaches can be integrated productively with empirically-focused social science.

1.6.1 Alife Modelling

This portion of the text aims first to describe the relatively new field of artificial life, and discuss its goals and implications. Once the background and import of Alife is established, then the shortcomings and theoretical pitfalls of such models are discussed. Given the strong association of Alife with biology and biological modelling, the theoretical discussion includes in-depth analysis of a framework for modelling in population biology proposed by Levins (1966, 1968). This analysis allows the theoretical implications of Alife to be placed in a broader context in preparation for the incorporation of further ideas from social science simulation.

1.6.2 Simulation for the Social Sciences

Agent-based modelling in the social sciences is a rather new development, similar to Alife. Social scientists may protest that modelling of various types has been ongoing in social science for centuries, and this is indeed true; however, this more recent methodology presents some similarly novel methodological and theoretical difficulties. This section of the text begins by describing the past and present of agent-based modelling in the social sciences, discussing the contributions and implications of each major development. Then, a discussion of current theoretical concerns in agent-based models for social science proceeds, describing modelling frameworks which attempt to categorise the various types of social simulations evident thus far in the field. Finally, an analysis of the problems of explanation via simulation which are particularly critical for the social sciences allows us to develop a broader understanding of these in a philosophical context.

1.6.3 Schelling's Model as a Case Study in Modelling

Schelling's model of residential segregation is notable for its impact and influence amongst social scientists and modellers (Schelling 1978). Despite the model's simplicity, the illustration it provided of a problematic social issue provoked a great deal of interest, both from social scientists interested in modelling and those formulating empirical studies. This investigation of Schelling will focus on how his model surpassed its simplicity to become so influential, and how this success can inform our discussion of agent-based modelling as a potentially powerful methodology in social science.

1.6.4 Developing a Model-Based Demography

Demography is an old discipline, originating from a major conceptual shift in the treatment of demographic events like birth, death and reproduction in the seventeenth century (Graunt 1662). In the years since, demography has gone through a series of methodological shifts, going from relatively straightforward early statistical work to present-day microsimulation and multilevel modelling approaches (Courgeau 2012). Simulation approaches to demography are now gaining popularity, particularly in areas such as migration, where simulation offers an opportunity to better understand the individual decision-making that plays a vital role in such processes (Anna Klabunde and Frans Willekens 2016). In Part III of this book, we will examine the methodological foundations of demography in detail, and investigate how simulation approaches can contribute to this highly empirical social science. We will present a proposal for a model-based approach to demography which attempts to resolve the conceptual gaps between the empirical focus of statistical demography and the explanatory and exploratory tendencies of social simulation. We will then discuss some applied examples of model-based demographic research and evaluate how these studies can influence our future efforts both in demography and in the social sciences more generally.

1.6.5 General Conclusions of the Text: Messages for the Modeller

By its nature, this text encompasses a number of different threads related to agent-based modelling to bring the reader to an understanding of both the positives and the negatives of this approach for the researcher who wishes to use simulation in the social sciences. Each of the three portions of the text builds upon the previous, with the goal of presenting modellers with both theoretical and practical concepts they can apply in their own work. Part I of the text demonstrates the problems and limitations of biologically-oriented agent-based models; such an approach is inherently theory-dependent, and modellers must be aware of this fact and justify the use of their model as a means to test and enhance their theories.

Part II of the text, focusing on simulation for the social sciences, describes the current state of this field and the various major disputes regarding its usefulness to the social scientist. This new type of modelling approach provides both new possibilities and new problems for the social scientist; the use of simulation can be a difficult balancing act for the researcher who wishes to provide useful conclusions. Thus, the social scientist interested in modelling must be knowledgable regarding these methodological difficulties, as analysed here, and avoid the impulse to produce highly complex models which may fall foul of the guidelines discussed.

In order to reinforce these points, we discuss an example of a powerful, successful, and simple model used within the social sciences: Schelling's residential

segregation model (Schelling 1971, 1978). In the context of the modelling frameworks discussed in the previous portions, Schelling's model provides a platform for examining those frameworks in a detailed fashion. Schelling's model demonstrates that the most useful models are not the most complex; simplicity and analysability are much more valuable than complexity for those who wish to understand the phenomena being modelled. In essence, no model can do it all, and a knowledge of the modelling frameworks under discussion here and their implications allows one to understand the necessary balancing act of designing and implementing a model in much greater depth.

Perhaps the most important balancing act related here is the tension between the need for a modeller to provide a theoretical backstory and the desire to minimise a model's theory-dependent nature. This is a common thread running throughout the text, whether the model in question is related to biology or social science. Modellers who create a model without a theoretical backstory that provides a context may find themselves creating a model with no relevance except to itself, while those who create a model with too great a degree of theory-dependence may find themselves warping their model into one restricted by theoretical bias, once again moving the model further from real-world applicability. The notion of balancing acts in model creation and implementation is often practiced intuitively by modellers, but yet this tension between backstory and theory dependence is rarely discussed explicitly by modellers in the literature.

Part III of the text brings us to the specific example of demography, a discipline where agent-based modelling approaches have begun to take hold in certain areas of enquiry. Building upon the foundations laid in previous chapters, the model-based demography framework described here presents a positive case-study for the integration of simulation with empirically-focused social science. Example models demonstrate how considered choices during model construction, development and implementation produces results that add to demographic knowledge without letting the simulations became unmanageable. The intention is for these models to serve as positive examples of pragmatic, considered modelling practices; each of them has limitations, but are still able to provide insight on the research questions they target.

1.6.6 Chapter Summaries

The analysis begins with an overall review of the philosophical issues and debates facing simulation science in general. Chapter 2 focuses on these general concerns, providing a summation of current thinking regarding issues of simulation methodology. A large portion of this chapter focuses upon the problem of validation of simulation results, which is an issue that is of great importance to the theoretical frameworks under examination. A further discussion of the difficulties inherent in linking the artificial with the natural provides a broader philosophical context for the discussion.

Chapter 3 picks up at this point, focusing on the efforts of Alife researchers to make the artificial become 'real.' After introducing the concepts of 'strong' and 'weak' artificial life, the significance of these two perspectives is discussed in the context of the still-developing philosophical debates of Alife practitioners. A central theme in this chapter is the drive to develop empirical Alife: simulations which can supplement datasets derived from real-world data. Taking into account the problems of validation discussed earlier and the two varying streams of Alife theory, a possible theoretical framework for underwriting empirical Alife is developed.

Chapter 4 moves on to population biology, drawing upon modelling frameworks developed within that discipline to strengthen our burgeoning theoretical backstory for Alife. Levins' three types of models, described in his seminal 1966 paper, provoked a great deal of debate regarding the strengths and weaknesses of modelling in biology, a debate which continues to rage today. After an analysis of Levins' three types, an expanded version of his framework is developed in the hope of providing a more pragmatic theoretical position for the model-builder.

Chapter 5 focuses mainly upon a review of the current state-of-the-art in simulation for the social sciences. Beginning with a look at early models, such as Schelling's residential segregation model (Schelling 1978) and Axelrod's iterated prisoner's dilemma (Axelrod 1984), we move on to more current work including Cederman's work within political science (Cederman 1997). This leads to a review of common criticisms of this growing field and the methodological peculiarities facing social-science modellers. These peculiarities are not limited to social simulation, of course; social science as a whole has unique aspects to its theory and practice which are an important consideration for the modeller.

Chapter 6 then proceeds with an analysis of social simulation in the context of the theoretical frameworks and issues laid out thus far. First, an overall analysis of Alife and related modelling issues in population biology gives us a set of frameworks useful for that particular field. Next, these theoretical concerns are applied to social simulation in the hope of discovering the commonalities between these two varieties of simulation science. This leads to a discussion of the possibility of using social simulation to drive innovations in social theory as a whole; the work of Luhmann is used as an example of one perspective that may prove valuable in that respect (Luhmann 1995). Finally, having placed social simulation within a theoretical framework, the debate regarding the usefulness of social simulation for social explanation is summarised and discussed.

Chapter 7 extends the analysis begun in Chap. 5 by utilising a case study: Schelling's well-known residential segregation model (Schelling 1978). Schelling's model is noted for its simplicity: residential segregation is illustrated by a single rule applied to individual agents on a simple two-dimensional grid. This chapter investigates the reasons behind the powerful impact of Schelling's abstract formulation, placing the model in the theoretical constructs described thus far. The implications of Schelling's model on social theory is also discussed, with reference to the Luhmannian modelling perspective described in the previous chapter.

Chapter 8 offers a conclusion to the arguments laid out in Parts I and II. Having examined Alife modelling, modelling in biology, and social simulation, future directions for substantive modelling works are proposed. In the context of social simulation specifically, the problems of validation and explanation introduced earlier are revisited. The overall questions of methodological individualism in social simulation are investigated as well, with an eye toward developing methods of simulation which can transcend the perceived limitations on the explanatory power of social science models. Having used Schelling as a case study for the modelling frameworks under discussion, this chapter will also discuss how other modelling methodologies may fit cohesively into these frameworks.

Chapter 9 marks the beginning of Part III, in which we delve into the application of agent-based modelling to the specific discipline of demography. This chapter describes the historical evolution of the field, detailing the cumulative development of four successive methodological paradigms. From there we propose a methodological framework for a model-based demography, in which simulation helps demographers to overcome three key epistemological challenges within the discipline and helps avoid the insatiable 'beast' of over-reliance on detailed demographic data.

Chapter 10 moves beyond theoretical aspects of demography and dives into the practice of agent-based modelling in the field. We begin by discussing two examples in brief: Axtell et al.'s model of the decline of the Anasazi (Axtell et al. 2002); and Billari's Wedding Ring model of partnership formation (Billari et al. 2007). For our third, more detailed example, we will examine the Wedding Doughnut – an extended version of the Wedding Ring model which incorporates statistical demographic methods and adds a simple representation of individual health status (Silverman et al. 2013a; Bijak et al. 2013). Sensitivity analysis using Gaussian process emulators is also introduced as a means of understanding the impact of model parameters on their interactions on the final output of interest.

Chapter 11 focuses exclusively on a single model: the Linked Lives model of social care supply and demand (Noble et al. 2012; Silverman et al. 2013b). This model is a significant leap forward in complexity compared to the Wedding Doughnut, incorporating a simple economic system, spatial elements, partnership formation/dissolution, social care need and provision, and migration. We examine the model in detail, including another sensitivity analysis using Gaussian process emulators, and discuss how the strengths of this model can serve as a useful exemplar for future modelling efforts in demography.

Finally, Chap. 12 summarises our findings in Part III and links them to the theoretical discussions presented earlier in the volume. We evaluate the current state of model-based demography, and discuss how the development of this approach can inform efforts to bring agent-based modelling to other areas of the social sciences. Ultimately we will take model-based demography as a positive example of a discipline taking new methods and weaving them gradually and thoughtfully into the broader tapestry of demographic research. Demography benefits particularly from having a cumulative approach to methodology over the last three and a half

centuries. Other disciplines can benefit from the insights presented by model-based demography, and in turn develop new approaches to simulation that may strengthen other areas of social science alongside demography's focus on empirical relevance.

1.6.7 Contributions

The major contributions of this text lie within its philosophical and methodological study of modelling within both artificial life and the social sciences. These analyses provide a novel perspective on agent-based modelling methodologies and their relationship to more conventional empirical science. Other elements of the text present a sort of anthropological study of modelling within these areas of science, in the hope of providing a more cohesive view of the use and impact of simulation in a broader context.

Elements of Chap. 3 were based upon a work published in the proceedings for Artificial Life IX; this work aimed to develop a theoretical framework for empirical studies in Alife by providing comparison with other, more established fields of science. Chapter 4 was based substantially on a paper written by myself and Seth Bullock describing the pitfalls of an approach to modelling that relies upon 'artificial worlds'; this work draws upon the papers of Levins, Braitenberg and others. Elements of Chaps. 4 and 5 were drawn from a paper by myself and John Bryden which was published in the proceedings for The European Conference on Artificial Life in 2007. This paper proposed a new means of social simulation which could provide a deeper insight into a fundamental social theory. Chapter 9 is based upon a collaborative paper written with Daniel Courgeau, Jakub Bijak and Robert Franck which was published in an edited volume on agent-based modelling for demography. Chapters 10 and 11 are based largely upon two collaborative papers written with members of the Care Life Cycle Project at the University of Southampton, which ran from 2010 to 2015.

In summary, this text provides a new synthesis of theoretical and practical approaches to simulation science across different disciplines of the social sciences. By integrating perspectives from Alife, biology and social science into a single approach, this text provides a potential means to underwrite the use of simulation within these fields as a means to generate new theory and new insight. Particularly in fields relatively new to simulation, such as social science, the acceptance of this methodology as a valid means of enquiry is a slow process; this text hopes to accelerate the growth of simulation with this field by providing a coherent theoretical background to illustrate the unique strengths of computational modelling, while simultaneously delineating its unique pitfalls. The detailed treatment of simulation modelling in demography will further illustrate how relatively disparate frameworks – in this case the data-centric demographic approach and the explanatory focus of agent-based modelling – can be combined to produce new avenues of productive enquiry.

References

Axelrod, R. (1984). *The evolution of cooperation*. New York: Basic Books.

Axelrod, R., & Tesfatsion, L. (2006). A beginner's guide to agent-based modelling in the social sciences. In L. Tesfatsion, & K. L. Judd (Eds.), *Handbook of computational economics, vol. 2: Agent-based computational economics*, page Appendix A. Amsterdam: North Holland.

Axtell, R. L., Epstein, J. M., Dean, J. S., Gumerman, G. J., Swedlund, A. C., Harbeger, J., Chakravarty, S., Hammond, R., Parker, J., & Parker, M. (2002). Population growth and collapse in a multi–agent model of the Kayenta Anasazi in Long House Valley. *Proceedings of the National Academy of Sciences, 99*(3), 7275–7279.

Bedau, M. A. (1998). Philosophical content and method of artificial life. In T. W. Bynum, & J. H. Moor (Eds.), *The digital Phoenix: How computers are changing philosophy* (pp. 135–152). Oxford/Malden: Blackwell

Bijak, J., Hilton, J., Silverman, E., & Cao, V. (2013). Reforging the wedding ring: Exploring a semi-artificial model of population for the united kingdom with Gaussian process emulators. *Demographic Research, 29*(27), 729–766.

Billari, F., & Prskawetz, A. (2003). *Agent-based computational demography: Using simulation to improve our understanding of demographic behaviour*. Heidelberg: Physica Verlag.

Billari, F., Aparicio Diaz, B., Fent, T., & Prskawetz, A. (2007). The "Wedding Ring": An agent-based marriage model based on social interaction. *Demographic Research, 17*, 3.

Cederman, L. E. (1997). *Emergent actors in world politics: How states and nations develop and dissolve*. Princeton: Princeton University Press.

Courgeau, D. (2012). *Probability and social science: Methodological relationships between the two approaches* (Methodos series, Vol. 10). Dordrecht: Springer.

Courgeau, D., Bijak, J., Franck, R., & Silverman, E. (2017). Model-based demography: Towards a research agenda. In A. Grow & J. Van Bavel (Eds.), *Agent-based modelling and population studies* (Springer series on demographic methods and population analysis, pp. 29–51). Berlin/Heidelberg: Springer.

Di Paolo, E. A., Noble, J., & Bullock, S. (2000). Simulation models as opaque thought experiments. In M. A. Bedau, et al. (Ed.), *Artificial life VII* (pp. 497–506). Cambridge, MA: MIT Press.

Epstein, J. (1999). Agent-based computational models and generative social science. *Complexity, 4*(5), 41–60.

Graunt, J. (1662). *Natural and political observations mentioned in a following index, and made upon the bills of mortality*. London: Thomas Roycroft.

Klabunde, A., & Willekens, F. (2016). Decision-making in agent-based models of migration: State of the art and challenges. *European Journal of Population, 32*(1), 73–97.

Klüver, J., Stoica, C., & Schmidt, J. (2003). Formal models, social theory and computer simulations: Some methodical reflections. *Journal of Artificial Societies and Social Simulation, 6*(2), 8.

Langton, C. G. (1992). Life at the edge of chaos. In C. G. Langton, C. Taylor, J. D. Farmer, & S. Rasmussen (Eds.), *Artificial life II* (pp. 41–91). New York: MacMillan.

Levins, R. (1966). The strategy of model-building in population biology. *American Scientist, 54*, 421–431.

Levins, R. (1968). *Evolution in changing environments*. Princeton: Princeton University Press.

Luhmann, N. (1995). *Social systems*. Stanford: Stanford University Press.

Noble, J., Silverman, E., Bijak, J., Rossiter, S., Evandrou, M., Bullock, S., Vlachantoni, A., & Falkingham, J. (2012). Linked lives: The utility of an agent-based approach to modelling partnership and household formation in the context of social care. In C. Laroque, J. Himmelspach, R. Pasupathy, O. Rose, & J. M. Uhrmacher (Eds.), *Proceedings of the 2012 Winter Simulation Conference*. Piscataway: IEEE.

Ray, T. S. (1994). An evolutionary approach to synthetic biology: Zen and the art of creating life. *Artificial Life, 1*, 179–209.

Schelling, T. C. (1971). Dynamic models of segregation. *Journal of Mathematical Sociology, 1*, 143–186.

Schelling, T. C. (1978). *Micromotives and macrobehavior*. New York: W. W. Norton.

Silverman, E., & Bryden, J. (2007, to appear). From artificial societies to new social science theory. In *The Proceedings of ECAL 2007*.

Silverman, E., & Bullock, S. (2004). Empiricism and artificial life. In J. Pollack, M. Bedau, P. Husbands, T. Ikegami, & R. A. Watson (Eds.), *Artificial Life IX: Proceedings of the Ninth International Conference on the Simulation and Synthesis of Living Systems*. MIT Press/Bradford Books.

Silverman, E., Bijak, J., & Noble, J. (2011). Feeding the beast: Can computational demographic models free us from the tyranny of data? In *Advances in artificial life: ECAL 2011* (pp. 747–754). Cambridge, MA: MIT Press.

Silverman, E., Bijak, J., Hilton, J., Cao, V., & Noble, J. (2013a). When demography met social simulation: A tale of two modelling approaches. *Journal of Artificial Societies and Social Simulation, 16*(4), article 9.

Silverman, E., Hilton, J., Noble, J., & Bijak, J. (2013b). Simulating the cost of social care in an ageing society. In W. Rekdalsbakken, R. T. Bye, & H. Zhang (Eds.), *Proceedings of the 27th European Conference on Modelling and Simulation* (pp. 689–695). Dudweiler: Digitaldruck Pirrot.