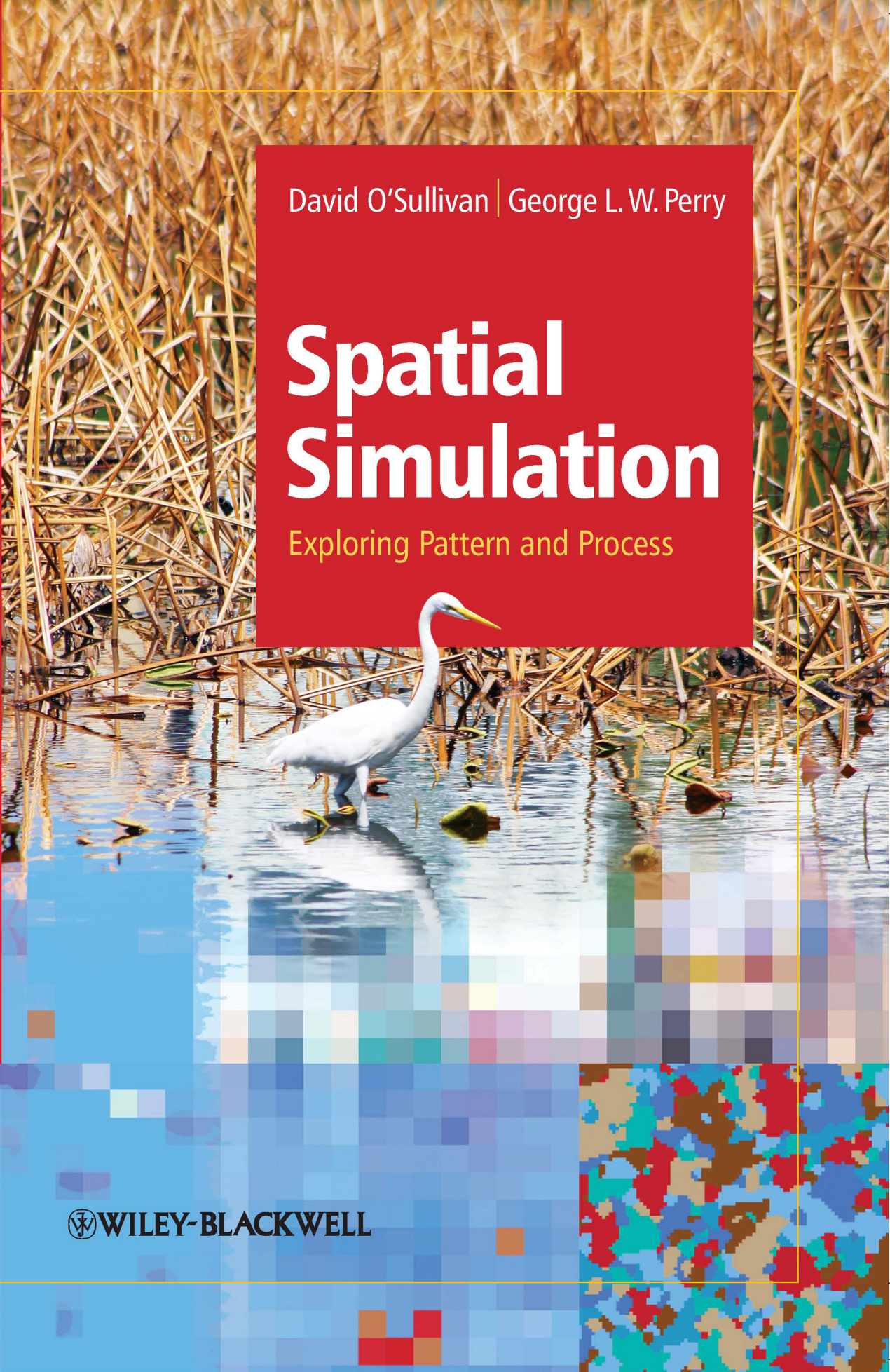
David O'Sullivan | George L. W. Perry
Spatial Simulation
Exploring Pattern and Process
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Spatial Simulation

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Exploring Pattern and Process

David O'Sullivan and **George L. W. Perry**

University of Auckland – Te Whare Wānanga o Tāmaki Makaurau, New Zealand

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To

Fintan & Malachy
and
Leo & Ash

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Foreword

Space matters. To answer Douglas Adams' question about life, the universe and everything, we need to detect and understand spatial patterns at different scales: how do they emerge, and how do they change over time? For most spatial patterns in social and environmental systems, controlled experiments on real systems are not a feasible way to develop understanding, so we must use models; but analytical mathematical models that address all relevant scales, entities, and interactions are also rarely feasible.

The advent of fast computers provided a new way to address spatial patterns at multiple scales: it became possible to simulate spatial processes and check whether or not our assumptions about these processes are sufficient to explain the emergence and dynamics of observed patterns. But then, as when any new scientific tool appears, results piled up quickly, perhaps too quickly, produced by thousands of models that were not related in any coherent or systematic way. There is still no general 'theory' of how space matters. Spatial simulation is thus similar to chemistry before the discovery of the periodic table of elements: a plethora of unrelated observations and partial insights, but no big picture or coherent theory.

This book sets out to change the current situation. The authors group spatial simulation models into three broad categories: aggregation and segregation, random walk and mobile entities, and growth and percolation. For each category, they provide systematic overviews of simple, generic models that can be used as building blocks for more complex and specific models. These building blocks demonstrate fundamental spatial processes and principles; they have well-known properties and thus do not need to be justified and analysed from scratch.

Using this book, model developers can identify building blocks appropriate for their own models. They can use the principles of model building and analysis that the book's opening and closing chapters summarize with amazing clarity. The authors demonstrate how all this works in a case study, in which a moderately complex spatial simulation model of island resource exploitation by hunter-gatherers is developed and analysed.

To facilitate the re-use of building blocks, this book itself is based on building blocks, using the free software platforms NetLogo (Wilensky 1999) and R (R Development Core Team 2012, Thiele and Grimm 2010, Thiele et al. 2012), which are widely used. All the models and R scripts are available on the internet as a model zoo, or model kit, for the spatial modeller. There (unlike at real zoos) you are invited to play with the zoo's specimens, and even to change and combine them!

This book helps establish a new culture of model building and use by reminding us that, as scientists, we need to see the forest through the trees and, with spatial simulation, the patterns in our explanations of spatial patterns. This book was badly needed. It makes us think, and play.

Volker Grimm,
Helmholtz Centre for Environmental Research – UFZ, Leipzig

Preface

This book had its genesis in three ideas.

The first, hatched at the 2006 Spatial Information Research Colloquium (or more precisely on the flight back from Dunedin to Auckland), is that for all their seeming variety, there are *really* only a limited number of truly different spatial processes and models of them. This modest proposal came up in conversation when we realised that we have both become good at anticipating what spatial models will do when they are described at conferences or workshops, and in the research literature. This perhaps debatable insight, followed by extended periods of omphaloscopy (often over a beer), eventually led us to the three broad categories of spatial model (aggregation, movement and spread) whose presentation forms the core of this book. As will become apparent, the dividing lines between these categories are hardly clear. Even so, we think the approach is a valuable one, and we have come to think of these as 'building-block' models. It is a central tenet of this book that understanding these will enable model builders at all levels of experience and expertise to develop simulations with more confidence and based on solid conceptual foundations. Belatedly, we have realised that the building-block model concept has much in common with the notion of 'design patterns' in computer programming and architecture.

The second insight, gleaned from several years' teaching a class where we require students to develop a spatial model on a topic that interests them, is that we (the authors) had picked up a lot of practical and usable knowledge about spatial models over the years, but that that knowledge is not easily accessible in one place (that we know of). This realisation took some time to dawn. It finally did, after the umpteenth occasion when a group of students seeking advice on how to get started with their model were stunned (and sometimes a little grumpy) when the seeming magic of a few lines of code in NetLogo (Wilenksy, 1999) or R got them a lot further than many hours of head scratching had. Examples *par excellence* are the code for a simple random walk in NetLogo:

```
to step ;; turtle procedure
  move-to one-of neighbors4
end
```

or for a voter model:

```
to update ;; patch procedure
  set pcolor [pcolor] of one-of neighbors4
end
```

It is easy to forget how much hard-earned knowledge is actually wrapped up in code fragments like these. Having realised it, it seemed a good idea to pass on this particular wisdom (if we can call it that) in a palatable form. The numerous example models at http://www.patternandprocess.org that accompany this book aim to do just that. A closely related motivation was the steady accumulation of fragments of NetLogo in a folder called 'oddModels' on one of our hard drives: 'Surely', we thought, 'there is some use to which all these bits and pieces can be put?!'

Finally, while the building-block models that are our central focus are in some senses simple, they are deceptively so. In that most understated of mathematical phrases, these models may be simple, but they are 'not trivial'. The thousands of papers published in the technically and mathematically demanding primary literature in mathematics, physics, statistics and allied fields attest to that fact. Unfortunately, this also means that students in fields where quantitative thinking is sometimes less emphasised—such as our own geography and ecology, but also in archaeology, architecture, planning, epidemiology, sociology and so on—can struggle to gain a foothold when trying to get to grips with these supposedly simple models. From this perspective we saw the value in presenting a more accessible point of entry to these models and their literature. That is what our book is intended to provide.

The jury remains out on just how many building-block models there are: our three categories are broad, but we are painfully aware that our coverage is necessarily incomplete. Reaction–diffusion systems and network models of one kind or another are significant omissions. The relatively demanding mathematics of reaction–diffusion models is the main reason for its absence. And because networks are about spatial structure, rather than spatial pattern *per se*, and to avoid doubling the size of an already rapidly growing book, we chose not to fill that gap, albeit with reservations. Perhaps as 'network science' continues to mature we can augment a future edition. At times, we also wondered if there might be *only one* spatial model (but which one?). In the end, we decided that there are already enough (near) incomprehensible mathematical texts staking claim to that terrain, and that our intended audience might not appreciate quite that degree of abstraction. Our more modest second and third ideas are, we hope, borne out by the book and its

accompanying example models. Ultimately, how well we have delivered on these ideas is for readers to decide.

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George Perry was fortunate enough to receive a Charles Bullard Fellowship, which enabled him to spend seven months working at Harvard Forest; this was an immensely rewarding time, both personally and professionally, and gave him time and space to think about and develop material in this book. Thanks to all the people at Harvard Forest who helped make his time there so productive and enjoyable. Over the last 15 years GP has spent considerable time working with colleagues at the Helmholtz Zentrum für Umweltforschung (UFZ) in Leipzig on various projects. Interactions with people there, especially Jürgen Groeneveld, have coloured his thinking on models and model-making. GP has also received funding from the Royal Society of New Zealand's Marsden fund and from the NSF (USA), ARC (Australia) and the NERC (UK)—the research that this funding enabled has contributed to his views on models and modelling.

We have been ably assisted at Wiley by Rachael Ballard, Jasmine Chang, Lucy Sayer and Fiona Seymour. We are both grateful for supportive noises and comments from many colleagues, and particularly to Mike Batty, Ben Davies, Steve Manson, James Millington and students in the ENVSCI 704 class of 2012 for insightful comments on late drafts of various parts of the manuscript. Iza Romanowska spotted what would have been an embarrassing error at a

late stage, for which we are grateful. We are grateful to Volker Grimm for his kind words in the foreword. His work is a constant inspiration, and if this book delivers on even a few of the claims he makes on its behalf, we will consider it a roaring success! Conversations with many colleagues and students have improved the text at every turn. Any errors that remain are, of course, our own.

And finally, to those who have borne the brunt of it, our families: from David, heartfelt thanks to Gill, Fintan and Malachy for putting up with an often absent(-minded, and in body) husband and father for so long; and from George, to Nicky, Leo and Ash, for tolerating my peripatetic wanderings as I finished this book, thank you, arohanui, and I look forward to getting back to building hardware models with you!

Introduction

On the face of it, the literature on 'spatial modelling'—that is models that represent the change in spatial patterns through time—is a morass of more or less idiosyncratic models and approaches. Likewise at first glance, the great diversity of observed spatial patterns calls for an equally wide range of processes to explain them. Ball (2009) provides a useful classification of the patterns in natural and social systems.

Our view, and the perspective of this book, is that just as there is a manageable number of spatial patterns, and it is useful to classify them, a relatively small suite of fundamental spatial process models are useful in exploring these patterns' origins. These models we consider to be 'building-blocks', which when thoughtfully combined can provide a point of departure for developing more complicated (and realistic) simulations of a wide variety of real-world phenomena. As Chesson (2000, page 343) notes, albeit in a different context, 'The bewildering array of ideas can be tamed. Being tamed, they are better placed to be used.' We aim to show how building-block models can help to accomplish this task in the context of spatial simulation.

Organisation of the book

Here we set out the general plan of this book to assist readers in making best use of it. Broadly, the material is organised into three parts as follows:

Preliminary material in Chapters 1 and 2 presents an overarching perspective on models, and the process of model-making in general, and spatial simulation models in particular, that informs our approach throughout.

- **Chapter 1** reviews what dynamic spatial models are, and why and how they can be used across the wide range of disciplines that comprise the contemporary social and environmental sciences.
- **Chapter 2** introduces the concepts of pattern and process that are central to our understanding of the importance of specifically *spatial* simulation

models. We present these principles in the context of spatial point process models, at the same time showing how such static models can be made more dynamic, so providing a link to the kinds of models that this book focuses on.

Building-block models are introduced in Chapters 3, 4 and 5. Each of these chapters considers a particular class of spatial models in some detail, roughly grouped according to their qualitative behaviour and outcomes. Each chapter starts with some examples of the sorts of systems and contexts in which the models being considered might be applicable. The models themselves are then introduced, starting as simply as possible so that the chapters are reasonably self-contained and can be read as standalone treatments. Each chapter closes with an overview of how these simple models have been used as a basis for more complicated simulations in a range of fields.

Chapter 3 considers models that produce patchy spatial patterns most commonly referred to as 'aggregated' or 'segregated'. Such models can provide the stage on which other dynamic processes might operate.

Chapter 4 provides an overview of simple approaches to representing the movement of individuals and groups, starting with random walk models and developing these to look at foraging and/or search, and flocking behaviours.

Chapter 5 reviews a number of simple models of processes of spread or growth through spatially heterogeneous environments.

Applying the models in practice is considered from a number of perspectives, with a particular emphasis on spatial and temporal representation in Chapter 6, and model evaluation in Chapter 7. An example is presented in Chapter 8 to show how all these ideas can be combined.

Chapter 6 looks at some aspects of the representation of time and space in simulation models. While the building-block models of Chapters 3 to 5 do not necessarily raise many concerns in this regard, experience suggests that careful consideration must be given to these aspects when all but the simplest simulations are being developed.

Chapter 7 is the most technically demanding in the book, providing an overview of how models can be evaluated so that their outcomes can be used to make inferences about the real-world systems that they seek to represent. This chapter revisits many of the themes first introduced in Chapters 1 and 2 concerning the use of models in science.

Chapter 8 aims to bring together ideas from all of the preceding chapters through an extended worked example combining elements of all three building-block models. The model is implemented using some of the methods considered in Chapter 6, and its analysis deploys the tools of

Chapter 7. This example is more complicated than any in Chapters 3 to 5, and is comparable with examples that appear in the contemporary research literature. Even so, we believe that its complications are comprehensible viewed from the perspective of the earlier chapters, particularly the building-block models.

Finally, **Chapter 9** concludes with a brief summary of the book's main themes.

Using the book

This book could form the basis for several courses with different emphases in several fields. Our own jointly taught course 'Modelling of Environmental and Social Systems' has been taken by students of geography, ecology, environmental science, environmental management, biology, bioinformatics, archaeology, transport and civil engineering, psychology, statistics and chemistry, among others. While we believe that building-block models have a broad and general applicability, not all of the ground that we cover will be suitable for all these disciplines. Nevertheless, we hope that even if it is not the core text this book will be a useful addition to reading lists in courses in all of these fields. We also hope that the book will be a useful resource for those researchers making their first steps in spatial modelling outside the confines of a traditional course.

There are multiple pathways through this book depending on the context in which it is being read, and the reader's background and interests. In some situations, it might make sense to fill in the background in a little more detail than Chapters 1 and 2 allow, and also to cover Chapter 6 before approaching the building blocks themselves. Alternatively, it may make sense to just dive in and postpone the 'preliminaries' until after some models have been sampled in Chapters 3 to 5. For some readers the context will make more sense after some examples have been absorbed. Last, but certainly not least, Chapters 7 and 8 will invariably make most sense with all the other material already absorbed. For some readers Chapter 7 may be rather more demanding than the earlier material but we firmly believe that there is more to spatial modelling than appealing animations. If we are to make robust inferences about real systems using spatial models then we need to evaluate them rigorously, and this is what the tools introduced in Chapter 7 allow.

The literature on each of the building-block model areas is massive and growing rapidly, and it was not our intention to exhaustively review it. In a book of this size in places our treatment is necessarily limited, but we hope that any chapter of the book can provide a good point of entry to the literature for graduate seminars, reading groups or individual study.

Using the example models

This book is accompanied by many freely downloadable NetLogo (Wilensky, 1999) implementations of the models described in the text. The models can be found at http://patternandprocess.org. All of these models are released under the Creative Commons Attribution-NonCommercial-ShareAlike 3.0 License. Most of the figures were directly generated from these models using the excellent NetLogo-R extension described by Thiele and Grimm (2010). The analyses we present were all conducted using the freely available R environment (R-Development-Core-Team, 2012), some taking advantage of the RNetlogo library (Thiele et al., 2012) which allows NetLogo to run within R and so takes advantage of the latter's analytical capabilities.

How these models are used is up to the reader. We learned a lot writing them, and we trust that experimenting with them and examining the code will be a useful adjunct to the main text, and one that helps circumvent the difficulty of conveying inherently dynamic things on a static page. The point at which each model is discussed in the text is identified by a marginal turtle icon. We suggest that readers download the model in question when they first encounter it, and experiment with its behaviour while reading the associated text. It should be possible to reproduce patterns similar to those shown in the figures that accompany the discussion of each model. Examination of the code should clarify any ambiguity over the definition of the model. It should also provide ideas for how to implement the model, and its variants, in NetLogo or other platforms.

About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/osullivan/spatialsimulation

The website includes:

- Powerpoints of all figures from the book for downloading
- PDFs of tables from the book

1
Spatial Simulation Models: What? Why? How?

It is easy to see building and using models as a rather specialised process, but models are *not* mysterious or unusual things. We routinely use models in everyday life without giving them much thought, if any at all. Consider, for example, the word 'tree'. We may not exactly have a 'picture in our heads' when we use the word, but we could certainly oblige if we were asked to draw a 'tree'. The word is associated with some particular characteristics, and we all have some notion of the intended meaning when it is used. In effect, everyday language models the world, using concrete nouns, as a wide variety of categories of thing: cats, dogs, buses, trains, chairs, toothbrushes and so on. We do this because if we did not, the world would become an unfathomable mess of sensory inputs that would have to be continually and constantly untangled in order to accomplish even the most trivial tasks.

If you are reading this book, then you are already well-versed in using models in the language that you use everyday. We define scientific models as simplified representations of the world that are deliberately developed with the particular purpose of exploring aspects of the world around us. We are particularly concerned with *spatial simulation models* of real world systems and phenomena. Our aim in this book is to help you become as comfortable with *consciously* building and using such models as you are with the models you use in everyday language and life.

This aim requires us to address some basic questions about simulation models:

- What are they?
- Why do we need them and use them?
- How can (or should) we use them?

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It is clearly important in a book about simulation models and modelling to address these questions at the outset, and that is the purpose of this chapter.

The views we espouse are not held by every scientist or researcher who uses models in their work. In particular, we see models as primarily exploratory or heuristic learning tools, which we can use to clarify our thinking about the world, and to prompt further questions and further exploration. This view is somewhat removed from a more traditional perspective that has tended to see models as primarily predictive tools, although there is increasing realisation of the power of models as heuristic devices. As we will explain, our view is in large measure a product of the types of system and types of problem encountered in the social and environmental sciences. Nevertheless, as should become clear, this perspective is one that has relevance to simulation models as they are used across all the sciences, and becomes especially important when scientific models are used, as increasingly they are, to inform critical decisions in the policy arena.

After dealing with these foundational issues, we briefly introduce probability distributions. Our goal is to show that highly abstract models, *which make no claim to realism*, may nevertheless still be useful. It is also instructive to realise that probability distributions are actually models of a specific kind. Understanding the strengths and weaknesses of such models makes it easier to appreciate the role of more detailed models that take realism seriously and also the costs borne by this increased realism. Finally, we end the chapter by making a case for the more complicated dynamic, spatial simulation models that are the primary focus of this book.

1.1 What are simulation models?

You may already have noticed that we are using the word 'model' a great deal more than the word 'simulation'. The reason for this will become clear shortly, but in essence it is because models are a more generic concept than simulations. We consider the specific notion of a simulation model in Section 1.1.5, but focus for now on what models are.

The term *model* is a difficult one to pin down. For many, the most familiar use of the word is probably with reference to architectural or engineering models of a new building or product design. Until relatively recently, most such models were three-dimensional representations constructed from paper, wood, clay or some other material, and they allowed the designer to explore the possibilities of a proposed new building or product before the expensive business of creating the real thing began. Such 'design models' are often built to scale, necessitating simplification of the full-size object so that the overall effect can be appreciated without the finer details becoming too distracting. Contemporary designers of all kinds generally build not only *physical models*