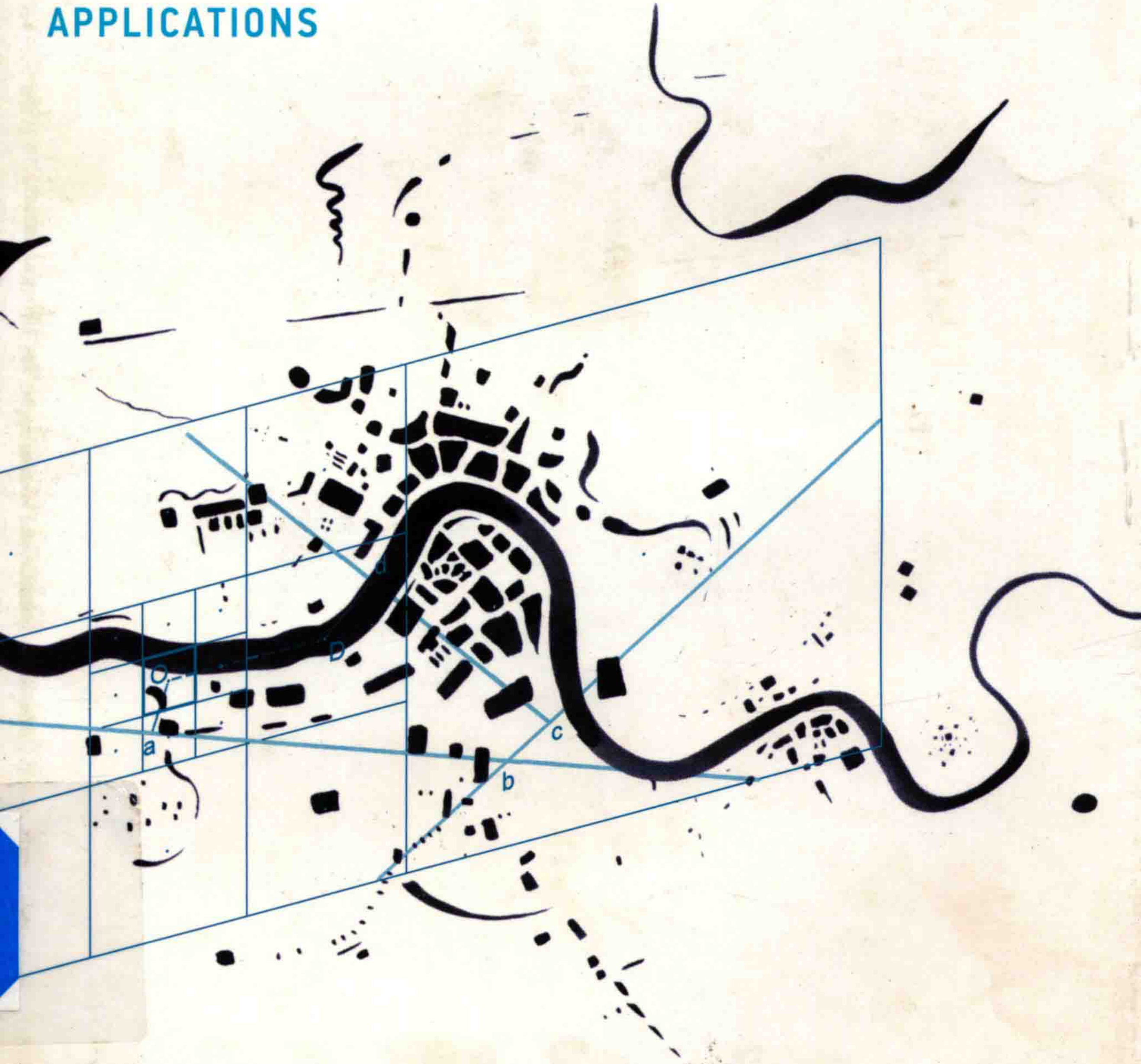
MODELING CITIES AND REGIONS AS COMPLEX SYSTEMS

FROM THEORY TO PLANNING APPLICATIONS

**Roger White,
Guy Engelen, and
Inge Uljee**



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Introduction

Cities and their regions, viewed over long historical timescales, seem to be in constant turmoil. They grow, decline, grow again, and continuously transform themselves. Over shorter timescales, the changes seem more measured and perhaps more orderly, but they occur continuously and they must either be accommodated or directed. This book is about modeling the spatial dynamics of urban growth and transformation. The aim is to achieve a better understanding of the evolving patterns of land use, population, and economic activity and to use that knowledge—and the models themselves—to increase the effectiveness of planning.

Our starting point is the observation that, in some sense, cities generate themselves—they are complex, adaptive, self-organizing systems. Of course, it is actually people who create cities, either individually or as organized into businesses, governments, and other institutions. But, for the most part, they do so inadvertently and unintentionally as they go about their daily lives. They aim to satisfy immediate needs—drop the children off at school, get to work, find a location for a new branch office, build a house to live in. They do not intend to build a city; that just happens. Even though, along the way, there are many acts of planning, these tend to be local, temporary, or incomplete. So, ultimately, a city emerges as the collective result of many individual events, most of which are not intended to be city building. But the acts of planning *are* intended to guide the development of the city, and these, to be successful, must rely on an understanding of the processes by which the city generates itself. Good models can help us to understand these processes and to work with them to create better cities.

If cities do in fact generate themselves, then the appropriate modeling framework is one based on the theory of self-organizing complex adaptive systems. This approach is already widely used in a number of fields from physics to ecology in order to model systems in which highly ordered structures appear spontaneously and then maintain themselves. Because the focus is on the dynamics of the systems being modeled, the approach is algorithmic. An algorithm can capture the step-by-step idiosyncratic process by which a city creates itself because an algorithm is an inherently executable description of a process. Furthermore, the description can be made as specific and detailed, and hence as realistic, as desired.

One of the most powerful algorithmic techniques for modeling dynamical systems is the cellular automaton (CA). The CA is an extremely simple and computationally efficient technique developed specifically to model spatial dynamics. It is also one of the most widely used platforms for research into the nature of complex self-organizing systems. The models that constitute the heart of this book are all developed within this framework, and most of them are CA based. They are, first of all, land use models: they show the evolution of land use at resolutions of tens to hundreds of meters, depending on the application. But the more advanced models also handle the dynamics of population and economic activities, either at the same resolution as the land use or at the scale of statistical or administrative regions. In addition, these models are commonly linked to or integrated with domain-specific models, such as economic, demographic, or hydrological models. The result is a family of models that give rich and realistic representations of the spatial dynamics of a number of urban phenomena.

More generally, the models in effect constitute a theory of cities as self-organizing systems. Because the models are relatively detailed and domain specific, they can function as serious scientific tools—tools that permit a confrontation of the implicit theory with reality in a detailed and rigorous way. These confrontations permit the models to be progressively improved and thus to provide a deeper, but also more practical, understanding of the spatial dynamics of cities and regions. Because of their power and realism, the models are now beginning to be used in a variety of situations as spatial decision support tools. They currently represent the most fully developed, detailed, and widely used tools for modeling urban and regional dynamics in a relatively realistic way.

Their very realism makes them seem mundane and straightforward. But under that realism lurks the wild and wonderful behavior that is characteristic of complex self-organizing systems. For example, like real cities, the models have open futures: they do not predict the future urban structure of a city, but rather an ensemble of possible urban structures, some of which may be quite different from others. Although spatial structure may appear straightforward, in fact, it is a complicated issue. It is not what you see on a map; it is *some* of what you see on a *set* of maps, and what you see depends on who you are. In other words, the self-organizing complex systems approach problematizes spatial structure. What at first seems simple is revealed to be complex, multifarious, and difficult to pin down. The underlying methodological and philosophical issues made explicit by working within the self-organizing systems framework are an important theme in this book because they underpin our understanding of the models themselves.

Spatial Structure

Cities are intricate socioeconomic entities dependent for their existence on their links with the natural environment. To fully understand them, we would need a socioeconomic-ecosystem theory of everything. Various disciplines are attempting to make progress toward this goal, but what is striking from our point of view is that most of them, whether in the natural or human sciences, consider spatial structure to be unimportant or incidental, if they recognize it at all. Perhaps spatial structure is not noticed because it is rather like the air we breathe: we are always and inescapably in it, so we take it for granted. We tend to notice these things only when something is wrong with them: we notice the atmosphere when it is polluted, and we notice the spatial structure when we can no longer function in it in the way we are accustomed to, as when we are routinely caught in traffic jams, or someone threatens to disrupt our neighborhood with a noxious facility. For most people, and most disciplines, the spatial structure is simply the setting and therefore unworthy of further consideration.

Nevertheless, cities *are* spatially structured, and clearly they function by virtue of that structure. The structure facilitates the economic, social, and cultural life of the city, and when the urban form becomes inadequate in some respect, so that it no longer acts as a smooth facilitator, the problem is noticed immediately by residents, businesses, and governments, who demand action. People think of their city in terms of spatial structure, often with a strong visual element, as described in Kevin Lynch's seminal book *The Image of the City* (1960). They map the city mentally into functional areas—industrial or residential areas, commercial strips, and so on. But they also map it in terms of social characteristics—rich and poor areas and ethnic neighborhoods. They map it, too, in emotional terms—threatening areas, areas of anomie, pleasurable areas. And they map it in terms of aesthetic characteristics—beautiful areas, ugly areas, districts redolent of history. All of these mental mappings affect the way people behave in the city—where they go, what routes they choose to get there, where they decide to establish businesses and public facilities, and where they decide to live and work. And these behaviors, in turn, affect the evolution of the spatial structure. This is the process of self-organization.

Continuous change of the urban spatial structure is certainly a prominent characteristic of cities, and one that is important to planners. But is it of any deeper significance? The answer would seem to be yes. Spatial structure seems to be an essential aspect of the emergence of complex, functional systems of every sort. The original work in the theory of self-organizing systems, Ilya Prigogine's investigation, during the 1950's and 1960's, of far-from-equilibrium chemical systems, focused on the appearance of macro-scale—that is, visible—spatial structure in reacting chemical systems. The canonical example is the Belousov-Zhabotinsky reaction, in which a variety of visible patterns—concentric circles, spirals, or multi-armed spirals—can appear when a reaction takes place in a shallow dish and the relative concentration of chemicals is maintained far from equilibrium (Nicolis and Prigogine, 1989). As Prigogine's group and others extended their work to examine the phenomena of self-organization in other fields, from biology to urban systems, they continued to focus on spatial structure. The implicit message is that spatial structure is both a defining characteristic and an essential factor in the emergence of complex systems, whether physical, chemical, biological, social, or economic, and this is certainly the case with cities. All of these systems come into existence by virtue of processes that create a spatial structuring of their constituent elements; their functionality depends on the pattern of that structuring, and different patterns yield different systems with different functions.

Of course, the constituent elements are also important. The people, businesses, and institutions that collectively constitute the spatial structure have their own characteristics and dynamics that are essential to the system, and these are the characteristics that are studied by the corresponding disciplines—demography, sociology, economics, organization theory, and so on. As much as possible, we need to incorporate the domain knowledge from these other disciplines into our models of spatial dynamics. Doing so not only improves the richness and reliability of the models; it has the bonus of integrating these other domains with one another through the spatial dimension because interactions are almost always locationally specific. Similarly, models of spatial structure enable a fully integrated treatment of natural and human systems, something that has otherwise proven difficult to achieve except in very crude ways.

Historical Studies of Urban Form

The dynamical, complex systems approach to spatial structure has only been possible since computer-based modeling became feasible. Before that, studies focusing on spatial structure were necessarily descriptive, although they occasionally included a diachronic component or simple static models—the Chicago school of urban ecology, for example, was known for its formal models. An additional problem was that location-specific data were largely unavailable until well into the twentieth century. Essentially, the only urban spatial data available for most past periods consist of street maps from historical documents or archaeological excavations. Studies of the long-term evolution of urban spatial form therefore tend to be restricted to the evolution of the pattern of streets and roads, although it is not necessarily easy to assemble these data: the work of Bernard Rouleau (1967) on the history of the Paris street network bears witness to this. This approach is, of course, methodologically quite different from the one we follow using dynamic models, and substantively it is different in its focus on street patterns rather than land use and socioeconomic distributions. Nevertheless, for the very reason that it is eccentric to our concerns, it provides a way to see our modeling approach in a broader context, so that we can understand more clearly what is present only implicitly in our models, and what is not present at all.

Studies of urban form based on historical street patterns have for the most part been carried out by architects with an interest in the city, such as Spiro Kostof (1991), A. E. G. Morris (1972), and Aldo Rossi (1982), or by urban historians like Lewis Mumford (1961). A recurring theme of these writers is the influence of belief systems on the patterns that appear in street networks. Although the network of streets and roads serves the need for mobility, the form of that network is not simply functional; in many cases, it also expresses cultural values. For example, in Paris, beginning during the Renaissance and continuing into the baroque period, characteristic squares (*places*) appeared, along with radial streets and the beginning of the Axe historique running west from the Tuileries Palace; these new geometric patterns, contrasting with the irregular street pattern inherited from the medieval period, reflected the ideals of order and rationality that characterized the Renaissance. Ideals of the ordered landscape have continued to surface in urban planning projects, for example, in the City Beautiful movement in the United States during the first part of the twentieth century, in the design of new capital cities like Brasilia, and in the extension of existing ones, like the prolongation of the Axe historique, with its visual and symbolic importance to Paris, into the new business center of La Défense, beyond the city of Paris proper.

The desire for a landscape that reflects cultural ideals is perhaps seen most clearly in the rationalized landscape of the then-rural areas west and south of Paris, where in the seventeenth and eighteenth centuries the landscape architect André Le Nôtre and others created a network of rigidly straight *allées* to give structure to the countryside, supplementing the axial gardens and the ornamental canals that surrounded the palaces of the great nobles (figure 1.1). Some of the geometry of this landscape, such as the radiating allées of the *pieds d'oie*, echo the geometry of the techniques used to implement the newly discovered laws of perspective. These laws also served to impose a kind of structural rationality on the visible world by providing a geometrical method for modeling visible reality in two dimensions. The geometrical nature of the relationship was implicitly taken to mean that the natural world itself had a hidden geometrical order. This conflation is explicitly displayed in Paolo Ucello's famous painting the *Battle of San Romano*, where the positioning of the spears expresses both a geometrical order inherent in the battle and the laws of perspective used to create the painting. In this connection, the camera obscura, another Renaissance invention, can be considered an early modeling technology, analogous to a computer, one that projected the three-dimensional world onto two dimensions in conformity with the laws of perspective and thus permitted an accurate

Figure 1.1
Baroque landscape of the Île-de-France; the shaded area is Paris. (Adapted from data in Benevolo, 1980)

representation of the visible world to be created in the form of a painting. It has even been suggested that the camera obscura has implicitly served as a paradigm of the positivist worldview that reality can be represented unambiguously and accurately—in other words, objectively—by means of a mechanical or formal model.

In the sense that our approach is concerned with models and theory, it might be considered neopositivist. Unlike architects and urban historians, however, we do not deal explicitly with cultural values and worldviews. But, ultimately, we should. We know from the work of both these groups that values and worldviews play a role in shaping the city. To point to a mundane contemporary example, the widespread urge in Anglo cultures to live in a single-family house surrounded by an extensive lawn contributes in a major way to low-density development and urban sprawl. Socioeconomic and demographic patterns are known to be affected by cultural values as well, though often in more indirect and subtle ways. In fact, it is likely that these factors are already present implicitly in our models because they are almost certainly among the determinants of the values of several of the parameters. A shift in social values would therefore be reflected in a need to recalibrate the models, with a consequent change in model behavior. A deeper and more explicit understanding of the relationship between cultural values and model structure, especially as expressed by parameter values, would at the very least allow us to make better judgments about the circumstances under which the models are likely to become unreliable. Explicitly including cultural effects might also enable us to make the models more widely applicable.

Since the time of classical Greece, the most common planned urban form has been the rectilinear grid. New cities in the Greek and Roman Empires, bastide towns in medieval Europe, and cities established in recent centuries in European colonies have all commonly been laid out on a grid. At times, the grid has had symbolic value, as in Chinese administrative centers, but, for the most part, it seems to have been adopted as a matter of convenience. In any case, like the elaborate Baroque geometries, it is a signature of the planned city. By the twentieth century, however, some architects concerned with urban form had begun to idealize the organic form of unplanned cities and to wonder how it could be achieved by design. The project to achieve an unplanned effect by planning was of course paradoxical. But the focus on organic form was a recognition of the fact that even unplanned cities are not formless, but are in fact highly structured in a way that cannot be captured by Euclidian geometry. In spite of their diversity, cities with an unplanned street pattern have a recognizable style that is somehow the result of incremental growth in the absence of a master plan.

In this contrast between the planned, Euclidian urban form and the unplanned, organic form, we see the opposition between planning and self-organization—between top-down and bottom-up processes. Much of the literature on urban form, especially that produced by architects, emphasizes the planned elements of urban form for obvious reasons: the planned elements are explicit and can be related to the cultural characteristics and historical events of the period, whereas organic form can at best be tracked diachronically, but always seems essentially contingent and accidental; in other words, little can be said about it. Many cities seem to have forms that are largely unplanned, even if, like Paris, they have planned inclusions. Even in North America, where the grid is considered the norm, if we zoom out to the metropolitan scale, the urban area as a whole is almost always "organic" in form, consisting of an irregular patchwork of different street patterns—grids, various curvilinear layouts, and unplanned networks—all held together by a system of major arterials that were either preexisting roads or later additions planned not to express a particular geometry, but rather to optimize traffic flow and connectivity at minimal cost. Thus, even though almost all urban areas have a form that reflects planning activities to varying degrees, globally, that form tends to be unplanned, organic, and self-organized. It is the self-organization of urban form that is the focus of this book.

Modeling in Context

Though we have been discussing urban form in terms of the pattern of streets and roads, that is not the focus of our treatment in this book. For the long sweep of urban history, the street layout is essentially the only aspect of urban form for which data are still available. Over the past century or so, however, with the appearance of cadastral and taxation records as well as census data, it has become possible to examine other aspects of urban structure, such as patterns of population density, ethnicity, income, and land use. Land use has been a particular focus of interest in recent years, largely because of the widespread availability of remotely sensed data, and it is the starting point for the models discussed in this book. But we go on to include population and economic activity in subsequent models, in order to arrive at a more comprehensive treatment of the evolution of urban form—a treatment that should also be more useful for both planners and others who must deal with the growth, organization, and reorganization that constitute every city's ongoing history.

Ironically, even though the availability of remotely sensed data was one of the main drivers of a surge of interest in developing models of urban land use change, such data are almost useless for distinguishing various urban land use classes. On the other hand, they do permit a number of rural land use and land cover classes to be distinguished. This provides an opportunity to model the city in its rural context—that is, to treat an entire region as the single, integrated system that it is. Cities and countryside are almost always treated as separate, unrelated phenomena, studied by different disciplinary specialties. If they are brought together in a single study, they tend to be treated as oppositional phenomena, as in Raymond Williams's book *The Country and the City* (1973). Yet each depends on the other, and some of the most pressing planning, political, and social problems arise from this interdependency. The loss of agricultural land to urban expansion, the intensification of agriculture in response to higher land prices in highly urbanized regions, and the loss of affordable housing for rural families as houses are converted to cottage use by urban families—all are manifestations of this interdependency. In fact, around large cities the distinction between urban and rural begins to break down as periurban land uses such as golf courses, rural recreation areas, and hobby farms come to dominate the countryside. As the models described in this book are extended to include rural phenomena explicitly, they will become increasingly useful for understanding and dealing with the problems arising from the urban-rural interdependency.

The progression from modeling land use to modeling land use together with the associated demographic and economic phenomena to modeling all of these plus agricultural activity and natural phenomena may seem like a grandiose project to create a model of everything, but that is not the case. Although modeling is a scientific tool, the activity of modeling is more an art than a science. When beginning to develop a model of some phenomenon, the most important step is deciding what to include. A model that includes too little is in a sense blind. It lacks information about factors that have a significant effect on the phenomenon being modeled. However well it may seem to perform in a specific situation and over the short run, such a model is not robust; it is unable to take into account ongoing changes in the situation to which it is being applied. On the other hand, including too much makes a model cumbersome and difficult both to apply and to understand. The art of model building lies in understanding how to include just enough, but no more. Of course, the judgment should be informed by knowledge of the situation; typically, there is at least some relevant research to suggest which additional phenomena may have an important influence on the ones being modeled and should therefore be included. But, ultimately, the knowledge base is never sufficient in itself to ensure the quality of the model. The quality depends on the informed intuition of the modeler, working with a deep understanding of both the situation being modeled and its wider context.

In almost every application of a model, the user has a particular focus of interest that is somewhat different from that of other users making other applications. In order to accommodate the widest range of applications, a model needs to be generic but customizable. Such a model is able to handle a wide variety of situations, as a very comprehensive model would, but to remain relatively simple in each individual application by giving minimal or no treatment to phenomena that are of little interest or importance in the particular case. For example, in the case of a comprehensive model that includes land use, population, economic activity, and agriculture, if the current application is focused on urban density, then the agricultural module can remain passive since there is no need to model agricultural dynamics. On the other hand, if the application is directed at understanding the impact of urban expansion on agriculture, then the agricultural dynamics module can be fully implemented, while the urban module can be simplified by using fewer economic sectors. Further flexibility can be achieved by using the core model as a platform for integrating standard preexisting models from other disciplines as necessary for specific applications. For example, the basic land use model described in chapter 6 has at various times been linked dynamically with an input-output model of the economy, a hydrological model in which infiltration and runoff depend on land use, and various traffic and transportation models. Since these linked components are typically well tested and well understood, they augment the capabilities of the land use model while contributing only a small amount of extra uncertainty about the performance of the full integrated model.

The models that are the focus of this book have been developed over a period of twenty-five years and are the product of the modeling approach just described. Although closely related—they are variations on a theme—they share a common core. Because their development was driven by the requirements of a variety of end users—clients in need of a model to assist them in addressing particular problems—they evolved as a family of models; the core model has therefore been repeatedly extended or modified, or linked dynamically to other models in order to meet the varying requirements of particular end-user applications. In every case, however, the models are based on the best domain knowledge available from urban and economic geography, regional science and transportation engineering, with models from other fields such as economics and hydrology borrowed as required. The aim is to keep the models rooted in the appropriate science even as their focus is determined by the needs of end users.

Of course, one of the goals of the modeling program is to extend the science—to deepen our understanding of cities and regions. Most of the existing analysis and theory in this area is static, and thus can tell us little about why and how cities and regions change. Since our models incorporate much of this theory but do so in the context of a complex self-organizing systems approach, a new, dynamic, theory begins to emerge, one that offers insights into the way cities structure and restructure themselves as they grow. From this perspective, it might seem that having clients determine the problems that the models address would interfere with the scientific goal. For the most part, however, this seems not to be the case. In a pure research setting—that is, in the absence of clients with often complex problems—it is easy to simplify the problems unduly in order to deal with them in a clean, precise, and apparently scientific fashion. The result can be a rather artificial, sterile treatment. Client-driven research keeps the research in contact with real, complex situations, and thus forces attention on unanticipated but useful problems. The research is messier, but the results, in the end, are better.

Modeling for Complex Self-Organizing Systems

Classical science values simplicity in theory backed up by rigorous testing, but this is an untenable position in the disciplines that deal with complex systems. Indeed, disciplines that have opted for simplicity or mathematical rigor in theory, such as economics, have effectively abandoned empirical testing. The only serious scientific alternative, as we will argue in the chapter 2, is to immerse the theory and the models in empirical complexity. Though it seems messy and its results often inconclusive, this approach reflects the nature of the phenomena that we are trying to understand. Formal complexity theory offers some hope for simplicity amid the complexity. A basic premise is that complex structures can be generated by simple processes; in principle, therefore, we might hope for a simple model that can generate a complex city. In fact, we find that this is indeed possible—up to a point. Or, really, up to two points. The first qualification is that the simple model generates not just a complex city, but many complex cities, which, according to the standard interpretation, represent the many possible cities the current city could become. If we assume that the future is open, that is, constrained but not entirely determined, then the fact that the model generates many possible futures for the city is not a fault but a strength: the model captures not just the complexity of the city but also the openness of its future. The second qualification is that real cities are not just complex, but complicated. They integrate many different phenomena, any one of which might be modeled as a complex self-organizing system. But if we hope to understand real cities through our models, then the models must include at least several of the most important phenomena. That makes them complicated. Both the open futures and the multiplicity of relevant phenomena mean that rigorous tests of the models are impossible. Results of validation tests are indicative, but usually not conclusive. Given this situation, multiple applications and multiple tests are the best approach to building confidence in a model—in other words, we need to keep the model immersed in empirical situations and see how it works. In this approach, we build individual models, but, over the long run, taking into account past experience and new situations, we create one model after another; the models essentially evolve. Modeling thus mirrors the processes by which cities are structured: acts of model design are carried out on a continual basis, but, in the end, the model, like the city, largely structures itself in response to the empirical constraints encountered in the course of many applications.

Because an appropriate methodology for the complex self-organizing systems approach is still emerging, modeling in this context is a process of exploring new methodological territory. For example, what does it mean to validate a model of a system with open futures? We do not quite know. As yet, there are no well-tested standards, nor a fully developed logic of the situation. These issues are important, and good modeling requires that we be aware of them and work through them as reasonably as we can. When possible, we may even take a step or two toward resolving them.

Ultimately, then, when we work within the framework of complex self-organizing systems theory, we find ourselves traveling through the land of the Spanish poet Antonio Machado (1989), the land where

Traveler, there is no path to follow.
The path is made by walking.

In this land, it is important to keep looking around, to see as much as possible, so that as we travel we will make a path that is interesting and useful.