

# Chapter 3

## Defining Urban Science



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**Abstract** This introductory chapter provides a brief overview of the theories and models that constitute what has come to be called urban science. Explaining and measuring the spatial structure of the city in terms of its form and function is one of the main goals of this science. It provides links between the way various theories about how the city is formed, in terms of its economy and social structure, and how these theories might be transformed into models that constitute the operational tools of urban informatics. First the idea of the city as a system is introduced, and then various models pertaining to the forces that determine what is located where in the city are presented. How these activities are linked to one another through flows and networks are then introduced. These models relate to formal models of spatial interaction, the distribution of the sizes of different cities, and the qualitative changes that take place as cities grow and evolve to different levels. Scaling is one of the major themes uniting these different elements grounding this science within the emerging field of complexity. We then illustrate how we might translate these ideas into operational models which are at the cutting edge of the new tools that are being developed in urban informatics, and which are elaborated in various chapters dealing with modeling and mobility throughout this book.

### 3.1 A Science of Cities

There are many sciences that encompass our understanding of cities. In this introductory chapter, we seek to define the range of scientific disciplines and perspectives that underpin theories pertaining to urban form, social structure, and the built environment in contemporary cities. The science that we will present is based on abstracting the critical functions that determine processes of change that characterize cities, processes such as the way markets operate; the way goods, people, and information are distributed across networks; the economic rationale for the location of activities in cities; and the way these functions and processes grow and change as cities get

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bigger or smaller. There are many sciences of the city that are not included in our remit, such as those involving the physics of the built environment, the ecology of cities, and the way climate impacts on city form and function; and there are many aspects of the social domain such as political actions and social mixing that are not considered in this review. But it is important at the outset to be clear about the limits to this science (Lobo et al. 2020). The purpose of this chapter is to suggest a wide variety of scientific ideas that support the quest for establishing urban informatics. We loosely define it here as the technologies and tools as well as the data that enable our city science to be embodied in the models and simulations that are used to improve the management and planning of cities and regions across many different scales and topic areas (Batty 2019).

Urban informatics has emerged as a coherent field largely due to the scaling down of computers and sensors to the point where they can be embedded at very high densities in every part of the urban environment. This includes mobile devices that people activate and operate, as well as fixed sensors that record data pertaining to their functions, often in real time. Urban informatics thus covers a wide range of digital data, from that which is collected in traditional terms from universal or sample censuses at typically low frequencies such as years or decades, all the way to real-time big data streams that are captured at very high frequencies and which provide a portrait of how the city is changing continuously. This field not only covers data, but it also embraces the tools and models that are collectively referred to as urban analytics. In all these tools, we need good theory, and thus, it is the purpose of this chapter to sketch the rudiments of a city science that covers both low- and high-frequency processes in cities, as well as methods of representing and visualizing the form these processes take when we are able to incorporate them in models, simulations, and predictions.

Accordingly we begin by exploring the nature of the city as a system, which was the dominant way of articulating its structure and dynamics in the middle years of the past century. This will establish the key components of cities and how they function at different levels of organization arranged in hierarchical fashion. This then leads us to extend our knowledge to systems of cities, although in this book we will only occasionally refer to such extended systems when we explore cities at regional and national levels. In reviewing these ideas, we introduce the notion that cities can also be seen as systems that emerge from a multitude of local individual decisions, implemented from the bottom up. These generate order from the apparent chaos of non-coordination, and this grounds the study of cities and this science as one of the main exemplars of complexity theory. The theories that have emerged from this focus on systems and complexity are often referred to loosely as social physics in analogy to mechanical systems, and we review these before we develop two key constructs that define the essence of this science of cities: scale and size. The way a city's spatial form—often through its geometry—is reflected in its functions generates the key properties of cities that are articulated in theories about how cities function economically and socially. We then present these functions, linking these to the networks and flows that form the cement that binds the various subsystems, components, and the city's elements together. Many of these models form the basis

of operational applications, and we will note a wide variety of these simulations to give readers some idea of the range of possibilities in using simulation in urban informatics. We will then conclude with some speculations about how these theories, as viewed in terms of urban informatics, influence the distribution of different types of cities world-wide and the way in which they can be used to develop tools to improve the quality of life and sustainability of cities through the development of urban informatics.

### 3.2 City Systems and Systems of Cities

Up to the beginning of the industrial revolution, all cities evolved from some central location where people came together to trade or to rule. From ancient times, populations clustered around these central places and cities developed in such a way that competition for locating closer to the center depended upon the ability of those who engaged in production to capture sufficient demand for their goods to be able to outbid others with respect to the price of space and proximity. Although this model was distorted in the early industrial revolution with the exploitation of fossil fuels around which cities also grew, the notion of the city having a dominant core with bands of different land-use activities or land uses surrounding it, became the received wisdom for how cities came to be formed. As transportation routes bringing producers and consumers to the center to engage in trade could not be built everywhere, cities also developed in radial fashion, with the dominant model being the radially concentric form that was most clearly articulated by Park and Burgess (1925) in their classic studies of Chicago.

The system underlying this model is much more complex, in that different subsystems exist, each with a radially concentric form at different hierarchical levels. These form neighborhoods, districts, communities, villages, and even small towns within bigger cities, and as the city grows and evolves, these hubs or clusters become ever more differentiated. In short, these subsystems form highly structured networks which in turn mirror a hierarchy of different functions, each serving local areas. The kinds of models that have been developed, and are still widely applied, simulate flows of people and goods between different places within the city, using analogies from gravitation that mirror the increasing deterrence effects that distance imposes on movement. The standard model divides the city into different locations (or zones) which we can label  $i$  and  $j$ , and we assume that a generic flow between these locations  $T_{ij}$  is a direct function of the size of places  $i$ ,  $O_i$  and  $j$ ,  $D_j$  and an inverse function of the distance or some function of spatial impedance  $d_{ij}$  between them. The typical model is

$$T_{ij} \sim O_i D_j f(d_{ij}) \quad (3.1)$$

and this is still widely applied to simulate transportation in cities, migration between cities, flows of expenditure to retail centers, and many other flow systems that define how the subsystems of the city engage with one another across many different hierarchical levels. A key element in this new science of cities is that patterns of spatial interaction also reflect underlying networks, and that the activities at different specific locations can be simulated as being proportional to the flows that emanate from all locations. From Eq. (3.1), these accumulations of flow at different locations might be predicted as proportional to the relevant activities as

$$\left. \begin{aligned} P_i &\propto \sum_j T_{ij} \sim O_i \sum_j D_j f(d_{ij}) \\ P_j &\propto \sum_i T_{ij} \sim D_j \sum_i O_i f(d_{ij}) \end{aligned} \right\}, \quad (3.2)$$

where  $P_i$  and  $P_j$  might be defined as some measure of population size at their respective locations.

The models in Eq. (3.2) are in essence measures of potential—in analogy to gravitation once again—or accessibility, and measure the relative nearness of all places to each place in question (Stewart 1947; Hansen 1959). The models developed by Jin (Chap. 8), which measure hotspots with respect to income and GDP, are in this tradition. In fact, this generic model can be made subject to constraints on locations in various ways. The usual version of the model used for transportation modeling is to make sure the trip distribution produced by the model in Eq. (3.1) meets the constraints on the size of trips generated at origins and attracted to destinations. This is the so-called doubly constrained model. If there are constraints solely on the origins or the destinations, these are singly constrained models, and it is possible to use them to predict the cumulative flow of trips at origins or destinations; in this sense, these are location models. If there are no constraints on either origins or destinations, the model in Eq. (3.1) predicts the location of activities such as the populations given by Eq. (3.2). This is the unconstrained model. This family of models and other variants was introduced by Wilson (1971) and has become the de facto standard in spatial interaction modeling.

This link between location and spatial interaction is key to the science that we are referring to. We can in fact generalize these ideas to many cities—to systems of cities as Berry (1964) first referred to them—in that although functions such as retailing specialize across a hierarchy within individual cities, this same sort of differentiation exists between cities. It was Christaller (1933) who first defined the hierarchy of cities with respect to the different functions different-sized cities have, using the idea that the bigger the city, the more specialist services it could provide—largely through its division of labor. The population would demand more specialist services in the bigger cities, and this would imply that the bigger city would need a much bigger hinterland to capture this demand than smaller cities. This would then be reflected in the area of the hinterland and thus implies a hierarchy of cities based on nested hinterlands associated with different city sizes, and a decreasing number of large cities and their hinterlands as the demand for more and more specialist functions grew. Christaller

did two things with these ideas. He first demonstrated that this pattern of nested hinterlands could be observed in the relatively well-developed landscape of Bavaria, while his second contribution was to abstract these hinterlands into a regular hierarchy of hexagonal market areas that could be nested and which reflected a progression of ever fewer but bigger central places. In fact, the model is one of the cornerstones of human geography, and it is consistent with much of location theory (Isard 1956), with spatial interaction models, with network representations of cities, and with the development of urban economics (Alonso 1964).

If we order the cities in such a system by size from the largest to the smallest, we can then rank them, and when we examine this ranking, it is easy to show that these sizes follow an inverse scaling relation which is often assumed to be an inverse-power law. Of course, the frequency of cities of the same size increases with rank in this theoretical central place system based on regular-nested hexagons, but if we consider that some noise is always present in such an evolving system, then it is not difficult to imagine that we get a smoother continuum, and it is this that has been used to demonstrate a strong relationship between city size and rank. It was Zipf (1949) who first popularized this relationship, and we can give some form to this by first thinking about the size of the various neighborhoods within a single city using the model that we introduced in Eqs. (3.1) and (3.2). Let us assume that the destination activity in Eq. (3.2), that is,  $P_j$ , can be ordered from largest to smallest. Then, we can use the index  $1, 2, \dots, n$  to define these cities where  $P(1)_j = P(\max)_j$  and  $P(1)_j > P(2)_k > P(3)_z > \dots$ . We can dispense with the index  $j$  because we are now rank-ordering the locations with respect to size, not location. The formal relation which has been demonstrated many times in many places for locations within cities and also between cities themselves—Zipf’s Law or the rank-size rule—can thus be stated as:

$$P(r) \propto 1/r^\alpha \quad (3.3)$$

where  $r$  is the rank of the location or city with population  $P(r)$  and  $\alpha$  is a parameter which defines the slope of the power law. In fact, the strict form of Zipf’s law is where  $\alpha = 1$  but most applications suggest that this parameter differs from 1. This is due to the relative stage which particular cities have reached in the evolutionary process, the fact that the distribution of cities is not in a steady state, and the fact that the spatial regions over which the relationship is defined, are not usually closed in any sense.

### 3.3 Urban Growth: Urbanization from the Bottom Up

The models that define the city in terms of spatial interaction are essentially static, in that they articulate the workings of the city at a cross section in time. There is little concern for process other than developing average relationships that encapsulate the

entire historical development of the city at the given point in time, and there is little concern for urban growth and change. As soon as the models from social physics were applied and adapted to urban applications, there was a move to embed and extend them to deal with related dynamic processes. Some of these applications simply used the models to simulate a series of cross sections and to explore the time series that was generated, but some have been used to simulate the actual changes as increments in each time interval, which provides a more basic representations of the dynamics. However, these kinds of application do not embrace the fundamentals of urban dynamics, and other models which are essentially temporal have been adopted.

Many of these models articulate the city not as a mechanism but as an organism, evolving like a biological system rather than being manufactured like a machine. In this sense, cities are represented not as aggregates of populations but as sets of individuals—agents—that act purposively in making decisions pertaining to urban development. Thus cities develop from the bottom up rather than being organized or planned from the top down. There are many models of how city populations grow and change but in aggregate, it looks now as though world population, whose growth until quite recently appeared to be exponential or even super-exponential, is likely to become logistic with the total population stabilizing by the end of the century. This of course is one prediction too far, but it appears currently to be the most likely, and in some respects, the growth of cities is following a similar trend. Big cities are getting bigger, but they are achieving this by fusing with other cities, generating polycentric urban landscapes while still attracting population, but at a decreasing rate. Cities are thus fusing into larger urban agglomerations, but their dynamics is much more mixed than following simple exponential and capacitated-exponential curves. A number of models that illustrate chaotic patterns of urban growth have been suggested, and although none of these have been operationalized for real cities, other than as thought experiments illustrated by stylized facts, they have provided an arsenal of tools for studying nonlinear dynamical systems that underpin many of the tools and techniques presented in the rest of this book.

As cities grow in size, they change qualitatively, generating economies and diseconomies of scale that do not cancel each other out. As cities get bigger, they bring more specialized people together, and as central place theory reveals, the bigger cities are much more specialized and serve a much larger population than the smaller ones. Their economies of scale are reflected in the fact that big cities are more innovative, more creative, and consequently often more wealthy, and there is considerable evidence that as cities grow, they do indeed become more than proportionately richer, creative, and innovative. But at the same time, there are diseconomies of scale which relate to more-than-proportionately increasing levels of crime, lower incomes among the poorest, and increasing inequalities between rich and poor. These relationships are captured in the key relationship between the income of a city  $Y(t)$  and its population  $P(t)$  that can be written as:

$$Y(t) \sim P(t)^\beta, \quad \beta > 1 \quad (3.4)$$

where  $\beta$  is a measure of the economies of scale. If  $\beta < 1$ , then the model in Eq. (3.4) illustrates that income increases less than proportionately with population size. This in fact is unlikely, but if we were to break the population down into different groups, then the poorest group would have to get more than proportionately much greater when cities increase in size for the relationships in Eq. (3.4) to hold. This sort of model was originally developed to look at growth in biological systems, but it presents a good analog of economies of scale, and has been widely applied to examples of ancient and modern city systems as well as firms, individual incomes, and a host of related socio-economic phenomena (West 2017).

In fact, this allometric model has not been developed temporally for individual cities or sets of cities, and there is considerable debate about the effect of scale economies, as the underlying processes which lead to this are defined away by such models; as such they remain implicit in these formulations. In fact, there is still a dearth of dynamic models that represent the way cities evolve, although with the development of complexity theory, there are several key dimensions to the way we now characterize these dynamics. There are no well-worked-out dynamics that coincide with the processes that determine how cities grow and evolve, and this is as much because there are very few good, robust theories that we have been able to discover to date. This is also because of our inability to observe such processes at first hand and compile good data. Urban systems like many social systems are highly resistant to detailed observation and show a degree of invisibility that is much more problematic than in many physical systems where we are able to instrument most features of any relevance.

Complexity theory does, however, reveal certain features of cities that define the limits to our existing models. Cities are always in disequilibrium and this is the new normal, as if it was anything other than that hitherto. In fact, cities are far from equilibrium, in that equilibrium is an abstract concept that in some models represents a long-term steady state, but in most models cannot be defined and probably does not exist. As cities grow from the bottom up, patterns emerge at higher levels. Although there are features of self-similarity at these different levels that we can grasp and sometimes articulate in terms of fractal phenomena, it is often difficult to tie the patterns that we see in cities at different levels to specific bottom-up processes. In this sense, history is all important as we perceive an average randomness in how decisions about urban development are made at the lowest levels. Decisions are for the most part rational if they are unpacked to the level at which they become understandable, but the physical limits of the city and the way we interact socially are such that these constrain what is possible and enable the emergence of order at all levels. In this sense, history matters just as much as geography does. As we implied above, our models and theories need to rapidly reflect the fact that the systems we are dealing vary in space and time. Our abilities to improve the quality of life in cities must take account of such variations which of course reflect underlying human behaviors. In short, in any complex system, there is a degree of historical path dependence that reflects the fact that decisions, although rational, are not necessarily ordered in any obvious way.

There are some processes that are now quite well defined such as those that reveal remarkably clear organization based on decisions that are initially random. For example, the model of segregation first developed by Schelling (1978) demonstrates that if a population system composed of agents are initially randomly distributed, but these agents have distinct preferences to always live with as many of their own kind around them, then if agents begin to move when this is not the case, very quickly an extreme pattern of segregation can evolve. The degree of extremeness—like ghettoization or gentrification in modern cities—appears to be entirely unwarranted, given that the agents have a very mild preference to live side by side with those of their own kind (being quite content to have an equal number of their own kind as well as an equal number of other kinds around them). The reason for this segregation, then, is that there is no coordination at the micro-level. Individuals move of their own accord when they see those around them dominating the neighborhood. It is processes like these that we need to identify in cities because part of our quest to make cities less polarized, more efficient, and to increase the quality of life, are closely bound up with this kind of decision making.

All issues pertaining to complexity influence our current thinking about cities (Batty 2005), but the theories we have about how the city system functions are still quite rudimentary. Many of the models we have hinted at so far are being developed for individual sectors and distinct dynamic processes, and many are being adapted to deal with short- as well as long-term change in the high- as well as the low-frequency city. For example, in this book, there are several chapters that deal with mobility and new data sets that pertain to networks and flows, and the models in this chapter are reflected in these. To an extent, urban informatics is much more about tools, techniques, and models than about theories, although theory is essential to constructing the bigger picture of how this domain can improve our understanding, prediction, and design of future cities. In the next section, we will pull the ideas of the previous two sections together, emphasizing how these models can be consistently linked in terms of what we know about scale and size, networks, and flows.

### 3.4 Scale and Size, Networks, and Flows

To all intents and purposes, by the end of the century, everyone will be living in cities of one size or another, where the distribution of sizes will follow the rank-size rule. The biggest cities will be up to 100 million in population, but all of these will be urban agglomerations that consist of polycentric hierarchies of smaller cities, towns, and villages that have fused together. But as we have shown in the previous two sections, the size of a city can also be measured with respect to its local morphology, its geometry, and the distances that define the bounds over which people will interact intensively to enact the business of the city. Since the industrial revolution and the invention of new technologies for mobility and interaction, all cities are part of a global urban form where distances, travel costs, travel times, and like measures of impedance condition the interactions and networks that bind all cities together. In

short, we can no longer think of cities as being freestanding entities; they are now networked in ways that make it ever more difficult to disentangle them from one another.

The ideas that we have introduced all pertain to different levels of size and scale. A metropolitan area for example has a certain population size, a density which is some measure of size with respect to unit area, and various distances from its core to its boundary. There is a common force which relates scale to size, and this is referred to in statistical physics as scaling. In essence, it means that as a city grows in size, density, in the length of its perimeter, and in the distances travelled within it, we can identify a common scaling that enables us to represent these various properties with respect to size. As we change their size, then the quantities involve scale in a relatively simple way. We can demonstrate this quite easily with respect to the various models that we have introduced. Starting with the standard spatial interaction model in Eq. (3.1), we can now write it in more specific terms using the inverse-power function of distance as follows:

$$T_{ij} \sim O_i D_j d_{ij}^{-\gamma} \quad (3.5)$$

If we increase the scale of the city by a factor  $\lambda$ , which to fix ideas, we might consider being equal to 2, this will change the model to:

$$T_{ij} \sim \lambda^{-\gamma} T_{ij} \sim \lambda^{-\gamma} O_i D_j d_{ij}^{-\gamma} = O_i D_j (\lambda d_{ij})^{-\gamma} \quad (3.6)$$

We have doubled the distance, but the number of trips has not halved, for the nonlinearity applied in the model reduces the number of trips by the factor  $\lambda^{-\gamma}$ . If we define an inverse square law of distance  $\gamma = 2$ , then the number of trips reduces by a factor of 4. In the same way, if our model incorporated economies of scale  $\vartheta$  and  $\mu$  which we apply to the origin and destination attractors as

$$T_{ij} \sim O_i^\vartheta D_j^\mu d_{ij}^{-\gamma} \quad (3.7)$$

and if we scale these attractors by  $(\xi O_i)^\vartheta$  and  $(\varpi D_j)^\mu$ , then we can easily show that the trips also scale in a nonlinear way, but remain proportionate to the existing flows.

When we look at the distribution of population sizes and any of the cumulative flows that can be predicted from the model in Eqs. (3.5) or (3.6), we have also noted in Eq. (3.3) that these follow an inverse-power law in the form of the rank-size rule. If we scale the rank of the cities by a rate  $\alpha$ , then the rank-size relation becomes:

$$\lambda^{-\alpha} P(r) \sim (\lambda r)^{-\alpha} = \lambda^{-\alpha} (r^{-\alpha}) \sim P(r) \quad (3.8)$$

The same kind of self-similar scaling is evident in any power-law relationship such as the urban allometric relationship in Eq. (3.4). If the population in all cities grows by a factor  $\lambda$ , then

$$\lambda^\beta Y(t) \sim (\lambda P(t))^\beta = \lambda^\beta P(t)^\beta \sim Y(t) \quad (3.9)$$

It is also worth noting that several key relationships which emerge from urban economics, such as the relationship between the density of population, rents charged, and indeed income itself, vary with respect to distance in the city. The long-standing observation that densities and rents decline inversely with distance from the core of the city has been widely modeled using inverse relationships as either a negative exponential or a power law. The density  $\rho_i$  (population  $P_i$  divided by area  $A_i$ ) defined as

$$\rho_i = P_i/A_i \sim \exp(-\varphi d_i) \quad \text{or} \quad \rho_i = P_i/A_i \sim d_i^{-\varphi} \quad (3.10)$$

is also scaling, as a simple change in the scale of distance in either of these relationships in Eq. (3.10) would show. These relationships indicate that as size increases in cities, quantities such as income, the numbers of trips, etc., increase or decrease more or less than proportionately, and this indicates that as cities grow or decline, there are qualitative changes that are likely to change the kinds of informatics that are appropriate. This is certainly true of issues concerning economic development, the provision of transportation, and the ability of the city to generate wealth, innovations, and new industries (Bettencourt 2021).

In some senses, what we know about the pattern of locations and interactions in cities is reflected in the underlying networks that support them. There are a multitude of such networks, other than the most obvious and visible systems that transport people and goods using different technologies or modes, but many are hard to observe and measure, particularly those that involve information, such as email, Web access, social media, even telephone, television, and countless other media. All of these networks have scaling properties that suggest that the distribution of their hubs in terms of their indegrees and outdegrees—the number of links that enter or leave the hubs or nodes defining these networks—follow rank-size distributions, and the number of clusters in such networks by size also follow similar inverse-power laws (Barabási 2018). In many of the chapters in this book that deal with mobility, networks form the basis of the various simulations, and the properties introduced here are key to the way such flows are measured and modeled.

### 3.5 The Development of Operational Urban Models

The theories and models that we have introduced form many of the elements of more comprehensive urban models that deal with various sectors of the urban system. Most models developed so far tend to be those that deal with the low-frequency city, but some of these tools, particularly those dealing with flows and networks which involve transportation, are being developed to deal with movements over short periods of time, focusing on real-time movements, usually on a daily basis. There are at least

four classes of model that we can define as the pillars of urban science with respect to urban informatics: first, those that depend on aggregate populations and activities which we call land-use transportation interaction (LUTI models), physical urban-development models using cellular automata (CA models), agent-based models that deal with disaggregate populations of individuals moving and making decisions through time (ABM models), and dynamic models that deal with individual decision-making, focusing largely on mobility and geodemographics such as microsimulation models (Chap. 44).

The generic spatial interaction model in Eq. (3.1) and its derivatives, such as accessibility potentials in Eq. (3.2), lie at the heart of many land-use transportation models that essentially stitch together several such models to replicate the locations and interactions between many population and employment sectors of the urban system. These models were first developed as pure transportation models and then extended to deal with land uses and activities in the 1960s. The problems they encountered were due to limits on computation which have now largely disappeared, but more important were the limitations of good theory and of course data. Data still remain an enormous problem, for data on spatial movements have always been hard to get, notwithstanding new sources from real-time capture on mobile devices. The fact that such models and their variants only simulate the city at a cross section in time spurred the development of more dynamic urban models, and in the later years of the last century, models based not on simulating the dynamics of population and employment location but on urban land use more generally at the physical level were developed. These models were largely based on cellular automata whose roots lie in complexity theory and in physical diffusion processes (such as forest fires). Because they focus literally on the physical development of land-use change, they are not easily linked to the numerical characterization of the city in terms of population, employment, income, and related properties. As such, rather than providing operational applications, CA processes as articulated in this genus of model find their use in more specific processes such as traffic simulation at the level of detailed flows.

In the quest for better representations, much more disaggregate models are being built using two different but complementary approaches: agent-based modeling and microsimulation. In terms of ABM models, urban models formulated in this way at the operational level are highly detailed with large data requirements on the behaviors of individual decision makers, usually households and firms, but most suffer from difficulties over developing good theory for the key urban dynamics processes at work in cities. As such, many models tend to be pilots and demonstrations, prototypes used to illustrate what is possible, and very few reach the level of full operability. UrbanSim and PECAS are exceptions. The fourth class of model based on microsimulation uses techniques based on constructing synthetic populations which are more tolerant of the lack of data pertaining to individual behaviors. Such simulations reflect probability distributions pertaining to the attributes of individuals in a population, and such profiles are used to construct synthetic estimates of populations according to a series of conditional probabilities. There are two subtypes of model, the first being traditional microsimulation models reflecting population profiles in terms of geodemographics. The second set are rather different in that these have

been quite widely developed for transportation modeling. These are loosely referred to as activity models, where households generate decisions about trip-making over the course a day, and the probabilities associated with such decision making translate into trip patterns at a very detailed level, such that these are much more powerful than detailed traffic-flow models. MATSIM is one of the best-known such models, although others such as SimMobility, SimAgent, and so on have been developed. All of these models derive from TRANSIMS, the original Los Alamos microsimulation of traffic flow. There are a number of reviews of all these models, and the reader is referred to Batty (2008), Wegener (2014), and Moeckel et al. (2018) for definitions, theoretical expositions, and applications.

In the rest of this book, these dimensions of urban science map out into many areas of urban informatics, and it is worth noting some of the key chapters that relate to this science before we conclude. In terms of modeling, all four of the areas that we have just defined are covered in detail in the chapters at the end of the book, in Part 5 where Eric Miller deals with transportation modeling (Chap. 47), Anthony Yeh with CA modeling (Chap. 45), Andrew Crooks and his co-authors (Chap. 46) with agent-based modeling, and Mark Birkin (Chap. 44) with microsimulation. Mobility of course runs through all these themes and is dealt with from different perspectives in several parts of the book, particularly by Shih-Lung Shaw (Chap. 5) and Martin Raubal and his co-authors (Chap. 6) in Part 1, by Marta Gonzalez et al. (Chap. 11) linking mobility to urban science in Part 2, Chiang Kai-Wei et al. (Chap. 25) explaining developments in mobile mapping in Part 3, methods for spatial search by Liping Di and Eugent Yu (Chap. 37) in Part 4, and with respect to the visualization of movement data by Gennady Andrienko et al. (Chap. 40) in Part 5. Sybil Derrible et al. (Chap. 7) and Budhendra Bhaduri et al. (Chap. 18) examine energy and infrastructure in their contributions in Parts 1 and 2, respectively. In terms of an overview, urban informatics is such a broad area that many of the authors here develop the big picture from their own perspectives. But in particular, Helen Couclelis (Chap. 9) sets all this in context of the smart city in Part 1, and Michael Goodchild provides the wider perspective for how this whole area of urban informatics is addressing questions of new and big data and geographic information science in Part 6.

### 3.6 Future Directions in Urban Informatics

There are many aspects of urban systems which we have not addressed in this brief review of what constitutes urban science. There is a general question as to how the tools and techniques of urban informatics apply to different types and sizes of cities in different cultures and societies. Much of urban studies is focused on such comparative analysis from the point of view of social and economic differences, and there are implications for the use of urban informatics in different sizes of city with different social cultures, political regimes, and governance. In particular, the distinction between the Global North and Global South is important, and there are already attempts at extending the ideas of city science to these domains, as in the reports from Acuto et al. (2018) and Lobo et al. (2020). Urban science deals with

how we define cities in terms of their spatial scale and their boundaries, and in this sense, the size of the city is all important with respect to the kinds of models and techniques that spin off from the ideas introduced in this chapter and elaborated in the rest of this book.

The theories that we have hinted at in this introductory chapter are by no means complete and never will be. Cities are driven by individuals, and complexity theory tells us that they grow and evolve from the bottom up. If there is a hidden hand in this process, it is in the fact that we appear to be able to produce quite ordered structures from our actions that in many respects are quite independent of each other. How we intervene in such complex systems is highly problematic, and urban informatics is in the front line of how we move toward a planning system that is effective in developing more sustainable, equitable, and efficient cities. This book introduces a very wide range of tools that can be used at many points in the planning and policy process, and a major focus needs to be on developing models and techniques that are able to adapt to new changes that continue to beset cities, as well as new technologies that are being introduced ever more rapidly.

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