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Urban systems

In this first chapter, we propose a rough, synthetic view of cities, by retaining what we believe to be some salient features from a quantitative point of view. There are many books and reviews, giving countless details and figures about cities (in particular, the reader can consult the updated version of reports produced by the UN – see for example "World urbanization propects, the 2014 revision"), and instead of offering a long list of various properties of cities (which can be found in different books and reliable sources such as the Census Bureau for the US, the UN, the OECD, or the World Bank), we focus here on a small set of key figures and discuss important scales manifesting in cities.

Cities are complex objects with many different temporal and spatial scales, related to a large number of processes. While a small set of numbers is certainly not enough to describe the full complexity of cities, such numbers can nevertheless allow for quantitative studies and for a large-scale characterization of urban systems. There is much variety among cities in terms of morphology, population, density distribution, and also functions, yet despite these differences, we observe statistical regularities for some observables. Indeed, we can expect that large systems composed of a large number of constituents lead to collective behaviors characterized by statistical regularities. Another reason for this "universality" is the existence of fundamental processes common to all cities: spatial organization of activities and residences, mobility of individuals, and so on. One of the most challenging problems of a science of cities is then to identify the minimal set of mechanisms that describe the evolution of cities.

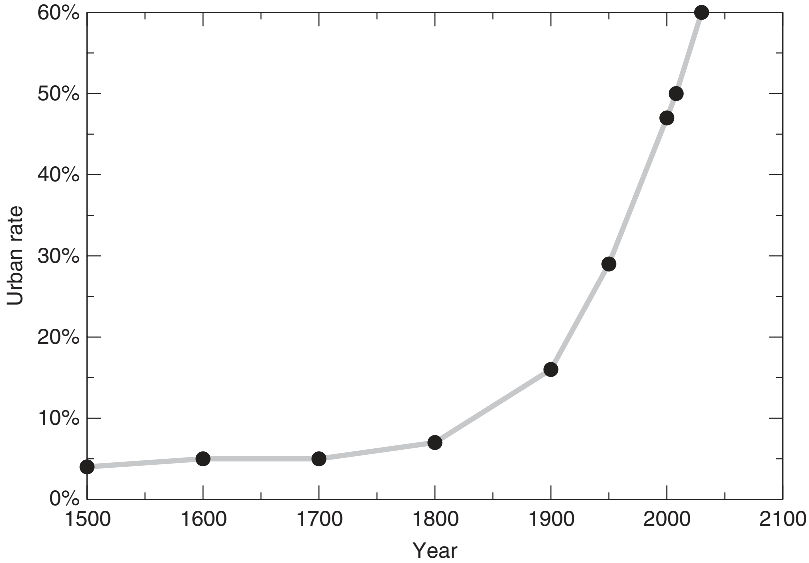

Figure 1.1. Evolution of the global urban rate (data from the HYDE history database http://themasites.pbl.nl/tridion/en/themasites/hyde).

1.1 A science of cities

1.1.1 The nature of the problem

A central issue in understanding urbanization is the large number of entangled, time-varying processes that generate cities. Many disciplines such as quantitative geography or urban economics have addressed some aspects of this problem and produced either very abstract models, or, at the other extreme, simulations with very large numbers of parameters designed for specific locales.

A proposal for a (new) science of cities that has recently emerged is based on an interdisciplinary strategy using ideas and tools from statistical physics of disordered systems, quantitative geography, and spatial economics. Key to this strategy is the extraction from data of universal facts that go beyond specific historical or geographical aspects of cities. These results will then be used to construct models with a minimal number of microscale ingredients leading to emergent collective behavior consistent with data.

This will be a landmark step for the construction of a science of cities and will allow for a long-delayed comparison of theory with empirical data. The results will impact many areas concerned with urban systems and will have practical applications for the planning of future cities. In particular, the primary goal is to understand the object "city" and to identify the dominant forces that shape its formation and evolution. Beneath these approaches lies the idea that the concept of

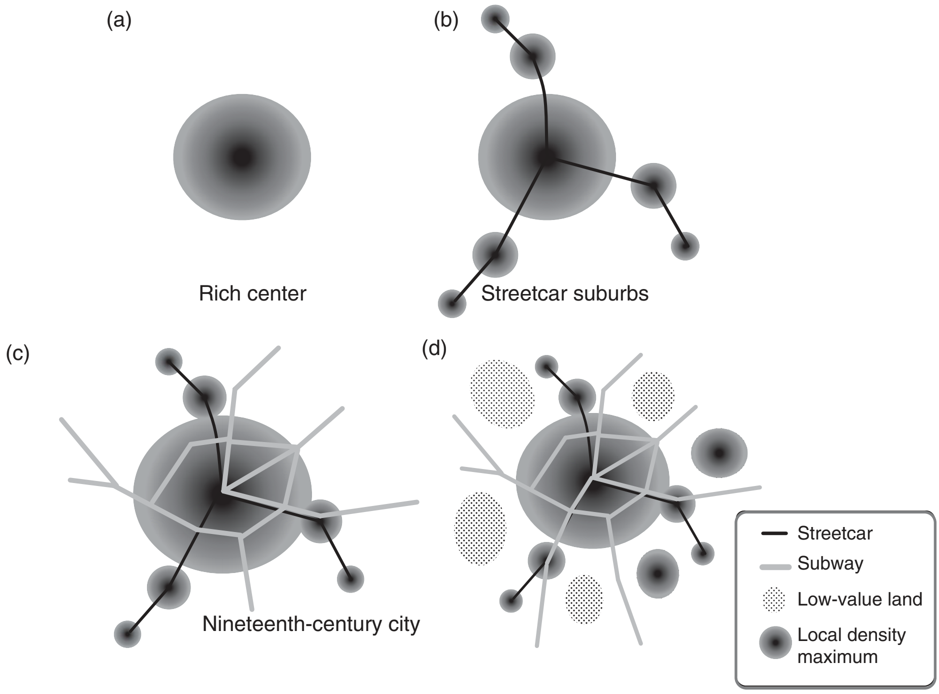

Figure 1.2. Illustration of the different phases for American cities (see for example Anas et al. (1998)). (a) Before the advent of streetcars and subways, businesses and manufactures concentrated in the center of the city, leading to a monocentric city with richer people living in the center. (b,c) Streetcars and subways allowed commuters to live further away from the CBD and around stations. (d) Cars increased mobility and former, cheap non-accessible zones rapidly became residential areas.

a city has some reality, albeit abstract, and that what we observe in the real world are simply specific instances of this entity on particular substrates, geographies, and histories.

The goal of a science of cities will be reached when, considering a specific case, we can basically say what will happen and which ingredients it is necessary to introduce in a model in order to get more detailed information and predictions.

First of all, we have to agree on the meaning of the word "understanding." For example, in the remarkable paper by Anas et al. (1998), there is a clear description of the time evolution of typical American cities (see Fig. 1.2): the high cost of communication led to concentration of industry and before 1850, personal transport was mainly by foot, resulting in a typical monocentric structure around the central business district (CBD) with income decreasing with distance from this center. The advent of electric streetcars led to the so-called "streetcar surburbs" structure where commuters live around stations that are radially dispersed from the CBD, a pattern that was later reinforced by the construction of subways. The automobile, which rapidly became available to the middle class, increased the mobility of individuals, and the low-value interstitial areas between streetcar (or subway) lines quickly became important residential areas. There is therefore a strong correlation between the transportation mode available to a large fraction of the population and the urban structure. The fact that different transportation systems appeared at different times, together with the durability of infrastructures, can then explain several patterns: older cities in the United States, on the East coast, have streets and buildings dating back to the era of their development as harbors, while more recent cities that developed during the automobile era have a spatial structure essentially determined by their highway systems. European cities have usually developed around medieval towns, but in contrast with US cities, the centers are usually still a mixture of residential and business areas, probably resulting from the large number of cultural amenities there.

This discussion shows that we "understand" some of the mechanisms leading to the formation of a city and governing its evolution. Here, understanding means that we can construct a consistent story, based on a few ingredients, that explains a selection of facts observed in reality. While this is somewhat satisfying, it is not enough for constructing a science of cities: indeed, we would like to assess quantitatively the impact of various factors, which means that we want to write mathematical relations between different quantities. The main point here is to identify the most important parameters, not only to understand the past, but also to be able to construct a model that indicates with reasonable confidence the future evolution of a city and allows the impact of various policies to be tested.

1.1.2 What is a city? Origins and definitions

From a very general point of view, cities exist in order to connect people. This primacy of interactions has now been acknowledged by many scientists, ranging from geographers (Batty 2013) to urban economists (see for example Thisse 2014). As pointed out by Brueckner et al. (2011), the explanation for the existence of cities varies a great deal from one field to another, depending on inclination. One goal of a science of cities is then to encompass these inclinations and to identify the driving mechanisms responsible for their formation and evolution.

It is still true to say that individuals interact face-to-face, and it is reasonable to follow urban economics that identify economies of scale and agglomeration effects as crucial factors in the formation of cities (see Duranton and Puga, 2004). Indeed, the total number of possible interactions between individuals grows very quickly as $P(P-1)/2$ (and probably saturates toward a finite value that corresponds to the Dunbar number of stable relationships; see Dunbar, 1992 and the recent validation via Twitter data, Gonçalves et al., 2011). Between two distinct groups of size P_1 and P_2 the number of possible interactions is $P_1 P_2$ and can thus also be very large. For a region of linear dimension R and uniform density ρ, the maximum number of possible direct interactions thus scales as $\rho^2 R^4$, showing the very strong effect of spatial localization and density. The desire to be at the same location, however, naturally induces competition and the appearence of a real-estate market.

Transport technology is the medium making these cities possible and is thus of crucial importance in the formation and evolution of cities. In addition to mobility infrastructure, we can list all the main elements that govern the formation and the evolution of cities: A network of interactions between individuals, flows of goods between firms, and infrastructure networks, making these interactions and flows possible. In addition, a city is never isolated but rather is part of a system of cities, at the national level, and now also at a global level (Bretagnolle et al. 2009).

There are obviously many other ingredients, such as policies, governance, and so on, and the numerousness of these elements is part of the problem in constructing a science of cities. Understanding how these different elements combine with each other and govern the evolution of urban systems will inevitably necessitate filtering some of these ingredients while keeping the most relevant of them. This huge variety of problems relating to cities concerns many different disciplines ranging from geography to applied mathematics, to transport, to urban economics, to qualitative social sciences. It is thus impossible to discuss all aspects of cities at once, casting some doubts on the possibility of a "unified theory" of cities able to describe all aspects of their evolution.

Even the apparently simplest question of how to define a city rapidly leads to significant problems. There are indeed various definitions of cities depending on era or country. The administrative definition, although straightforward, is outdated and does not capture urban sprawl. In order to remedy this, various agencies have proposed other defintions such as urban areas, MSAs (metropolitan statistical areas, in the US, FUAs (functional urban areas, as per the OECD), and LUZs (larger urban zones, in Europe), which basically define urban centers and connect them to other areas for which the commuter fraction is larger than a given threshold. These zones are defined such that they incorporate functional areas, but unfortunately are not necessarily consistent with each other. In addition, each of these definitions relies on a (small) set of parameters and it would be better to find a definition that can be used across time and also across space in order to compare different cities in different countries.

Another form of definition relies on non-ambiguous objects such as built-up areas and on the notion of contiguity. For example, Rozenfeld et al. (2008, 2011) introduced a bottom-up method for constructing cities by clustering areas from high-resolution data. More precisely, the City Clustering Algorithm (CCA) is

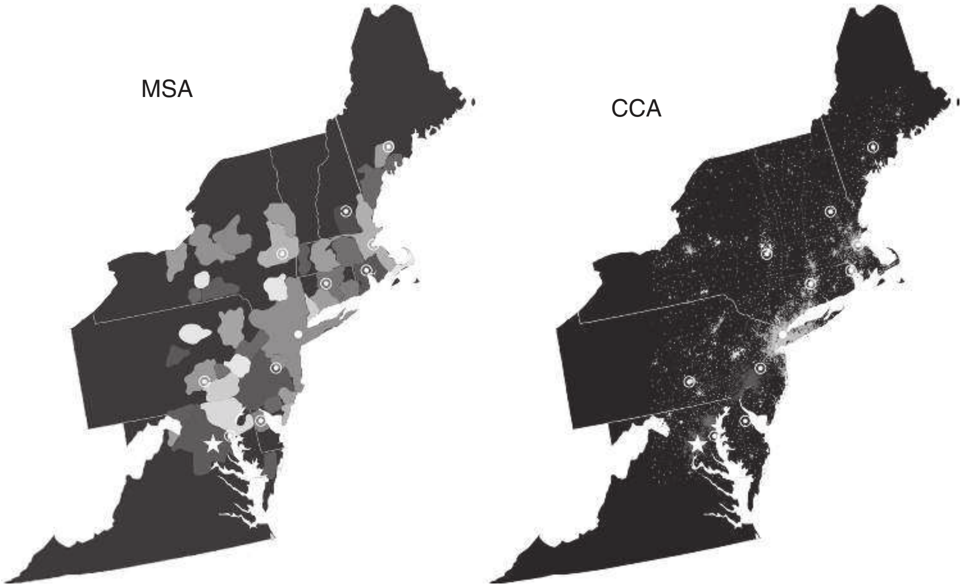

Figure 1.3. MSA for the northeastern US and the clusters obtained by the CCA algorithm with $\ell = 5$ km (the white circles denote the location of state capitals). Figures from Rozenfeld et al. (2011).

defined as follows: we first locate a populated area and then grow the cluster by adding all populated sites within a distance smaller than some level ℓ and with a population density larger than a threshold ρ^*. The cluster stops growing when no site at a distance less than ℓ and with density larger than ρ^* can be added. Rozenfeld et al. (2011) chose ρ^* and took ℓ in the range $[0.2, 4]$ (in km). It is interesting to note that this procedure leads to clusters that are not too different from actual MSAs (see Fig. 1.3 for an example).

Elaborating on these various ideas of percolation and functional areas, Arcaute et al. (2013) proposed a variant of the CCA algorithm to define cities. They use population density as the main parameter and start from a given unit of agglomeration ("wards" in the case of the UK). For a given unit, they cluster all adjacent units with density larger than a threshold ρ^* (see Fig. 1.4). Interestingly, there is a kind of "percolation transition" for a value of $\rho^* \approx 14$ persons per hectare above which cities merge together (in the instance, Liverpool and Manchester) to produce a very large cluster which contains the majority of the population ($> 70\%$) and represents the majority of the total area ($> 50\%$). For this density, the distribution of population follows a power law with exponent close to 2 as expected from Zipf's law and the clusters for this density threshold are therefore a good candidate for defining cities.

Figure 1.4. Cities obtained by the clustering algorithm for different density cut-offs. From top left to bottom right: $\rho^* = 40prs/ha$, $\rho^* = 24prs/ha$, $\rho^* = 10prs/ha$, and $\rho^* = 2prs/ha$. Figure from Arcaute et al. (2013).

In a second step, Arcaute et al. (2013) incorporate the notion of functionality through the number of commuters. Once they have detemined the clusters by density, they consider them as destinations of commuter flows (as long as their population is larger than a threshold N, in order to select important commuting hubs only) and add areas that are the origins of these flows. For each given ward, they then compute the fraction of individuals that commute to each of the destination clusters and the ward is added to the cluster that receives the largest flow if the flow is above a threshold τ_0. This procedure allows construction of cities with two parameters (N, τ_0) and testing, for example, the robustness of scaling exponents (see Section 7.4).

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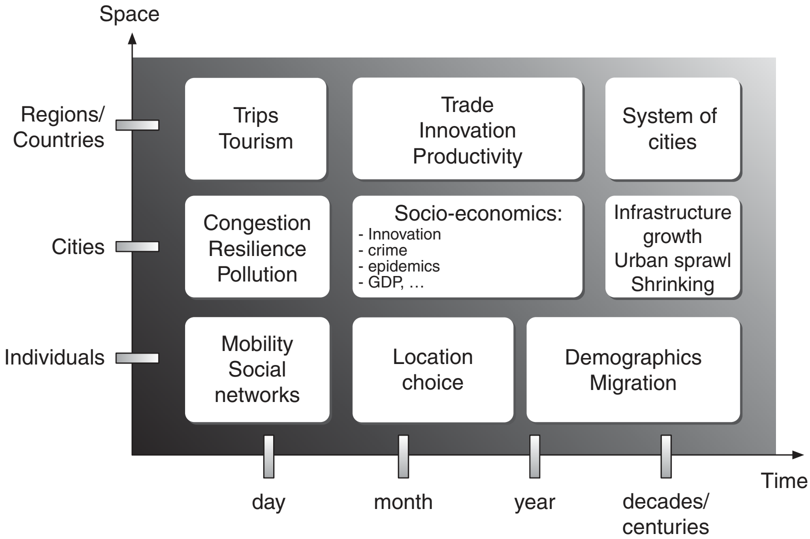

Figure 1.5. Schematic representation of processes occurring in urban systems according to their temporal and spatial scales.

1.2 Spatial and temporal scales

There are many different spatial and temporal scales in a city, each related to various processes occurring in these systems. It is not only the diversity of these scales that make the modeling of cities difficult, but also the large variety of agents and their impacts on the life and evolution of urban systems. We represent in Fig. 1.5 the most important processes and the order of magnitude of the spatial and temporal scales involved. We see that we have a wide spectrum of scales that are mixed together. This almost continuous spectrum makes it difficult to consider cities as being in equilibrium (see Chapter 2) but also to view these processes as decoupled from each other. This is a very important problem in city modeling and necessitates a careful discussion of spatial and temporal scales, acknowledging the possibility that various processes are interfering with each other.

We will now describe in more detail some typical scales and variations of important quantities for cities, such as population, area, and (population) density.

1.2.1 Population

Population is a critically important parameter for cities. Indeed, it is often assumed to be the explanatory variable, neglecting endogeneity issues. In many cases, however, knowing the population of a city reveals much about it (Pumain and Moriconi-Ebrard 1997) and seems to be a good starting point for a theoretical framework to understand how cities evolve as their populations grow. Eventually,

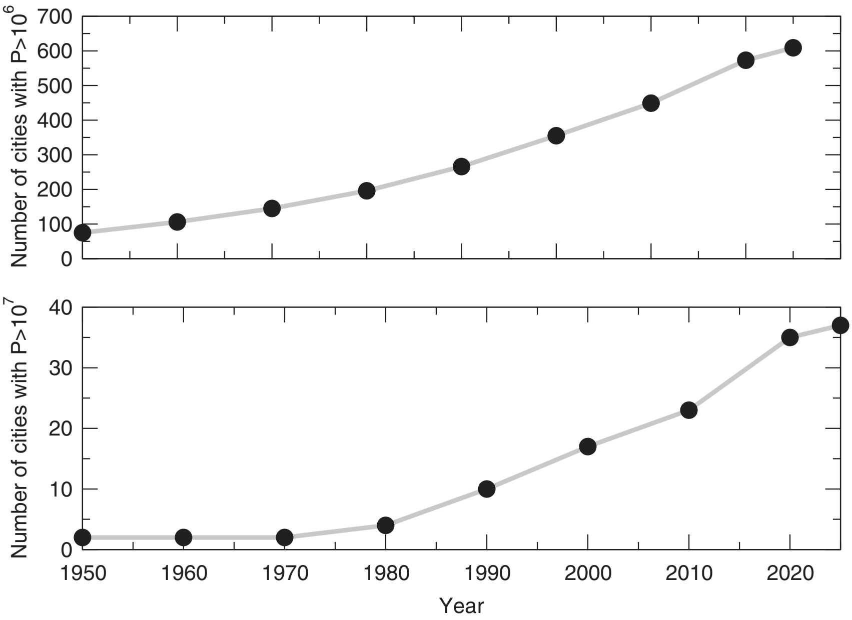

Figure 1.6. Evolution of the number of cities in the world with population larger than 1 million (top) and the number of megacities (with $P > 10^7$ inhabitants; bottom). Data from the UN.

a theory that endogenously describes the evolution of cities and their populations would mark a fantastic advance in our understanding of these systems.

We observe a large variety of cities around the world, with very different populations and growth rates. In this section we present a quick overview of the main facts regarding this quantity.

Size of cities

There is a wide variety of city sizes, from small towns with 10^4 inhabitants to megacities with populations greater than 10 million. Large cities and in particular megacities represent almost 10% of world urban population, and their number is growing (Fig. 1.6). We expect approximately 40 megacities in the world by 2020.

Concerning the structure and evolution of cities, we need to separate the developed countries from the developing ones. According to the UN Statistics division (see for example the Demographic Yearbook and World Urbanization Prospects for 2005 and 2011), for developed countries there is a decline in native-born population growth and it is estimated that about 1/3 of urban growth will come from migrations. The urban population – as shown in Fig. 1.7 – is essentially concentrated in small cities (in the range $[10^5, 10^6]$ inhabitants) with 30.5% living in cities with more than 1 million inhabitants. This has to

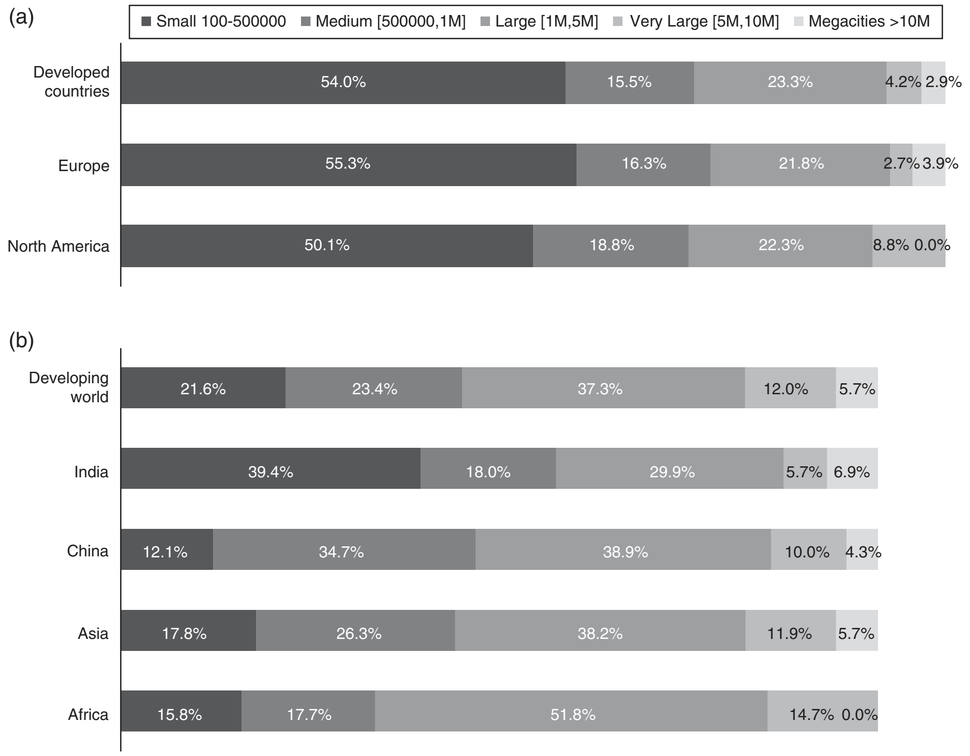

Figure 1.7. Distribution of the urban population in (top) developed countries and (bottom) developing countries. Data from the UN Statistics Division.

be contrasted with developing countries where there is still a strong pace of urbanization with an average of about 2% per annum (2015). Also, in these countries, urban dwellers live preferentially in large cities, with 54% of the urban population in cities with more than 1 million inhabitants.

Growth rates

Urban growth has different sources such as migration or birth. In developed countries, international migration will become the main source, while for developing countries it is the high birth rate that increases the city population. In China, however, the main source of growth is the migration from rural to urban areas. The growth rate of cities depends on their size; in Table 1.1 we show the results obtained by Bretagnolle et al. (2009). More precisely, if we distinguish developed from developing countries, we see that growth rates are distributed very differently. For developed countries, in a total of over 1,287 cities (with size larger than 100,000 inhabitants), 39.9% are declining, while 34.9% of the 1,398 developing-country cities (with $P > 100{,}000$) are experiencing rapid growth (see Fig. 1.8). For example, China in 2025 will have approximately 140 cities with more