Chapter 7
The Self Similarity of Human Social Organization and Dynamics in Cities

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7.1 Introduction

The issue of whether quantitative and predictive theories, so successful in the natural sciences, can be constructed to describe human social organization has been a theme of inquiry throughout the entire history of science. Aristotle was perhaps the first to write on the subject in ways that present clear scientific challenges that are still with us today. In Politics (Book I), he wrote

> [. . .] it is evident that the state [polis] is a creation of nature, and that man is by nature a political animal. The proof that the state is a creation of nature and prior to the individual is that the individual, when isolated, is not self-sufficing; and therefore he is like a part in relation to the whole.

The idea that cities (the "State" for Aristotle) are natural inevitable structures on which humans coalesce and thrive has suggested many metaphors for cities as natural organisms (Miller, 1978; Girardet, 1992; Graedel & Allenby, 1995; Botkin & Beveridge, 1997; Decker Elliott, Smith, Blake, & Rowland, 2000), or ecologies (Macionis & Parrillo, 1998). Modern sociological thought about the nature of urban life (Durkheim, 1964; Simmel, 1964; Macionis & Parrillo, 1998), especially in the United States (Wirth, 1938), was born largely out these analogies. Cities as consumers of resources and energy, and producers of organizational structures and waste have a clear counterpart in biological organisms. Therefore, it is interesting to ask to what extent these analogies are more than anecdotal. For instance, are analogies of cities as organisms, with specific metabolism, useful to establish quantitative expectations for their resource demands, environmental impacts and growth trajectories?

The idea that cities are emerging natural structures, that in some sense (to be demonstrated below) are independent of culture, geography or time, also suggests that there should be universal features common to all urban agglomerations (Wirth, 1938), which, in turn, may define an *average idealized city*. Such a city would be characterized in terms of quantitative indicators and would constitute the benchmark

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against which real cities should be measured, both in their successes and in their shortcomings. This concept of a quantifiable average city may be natural, even intuitive, to anyone who seeks synthesis among the huge diversity of urban social life and is implicit in many policy considerations (Wirth, 1938; Macionis & Parrillo, 1998). But its pursuit is often at odds with traditions in the social sciences that emphasize instead the richness and differentiation (Macionis & Parrillo, 1998; Durkheim, 1964; Simmel, 1964) of human social expression. The tension between these two approaches can only be diffused, in our opinion, by empirical investigations determining if average idealized characterizations of urban organization are supported by data, and can be synthesized as predictive theories of certain key features of human dynamics and organization.

Below, we will pursue and partially accomplish some of these goals. We will show that, when observed from the point of view of their rates of change, cities are approximately self-similar entities across entire urban systems (usually taken to be nations), and that these properties scale with population size in a manner that is independent of any particular reference scale. In this sense, knowledge of urban indicators for a city of a given size implies predictions for those of another, given only their population ratio. Because quantitatively similar scaling laws are a property of biological organisms (West, Brown, & Enquist, 1997; West, Brown, & Enquist, 1999; West, Brown, & Enquist, 2001; Enquist, Brown, & West, 1998), we will also be able to establish to what extent cities can indeed be understood in terms of biological organization, and specifically how human societies differ and transcend these structures.

The remaining of this chapter is organized as follows. We start with basic expectations for the behavior of cities, resulting from analogies to biological scaling. We then give a brief account of the initial quantitative studies that suggested that the framework in urban organization would be more complex. Following on these hints we give an overview of other urban indicators and how they scale with population. We then discuss the implications for growth from urban scaling relations and conclude with some speculations and directions for future work.

7.2 General Expectations from Biological Scaling

Before we started our empirical investigation on urban scaling we attempted to translate the metaphor for cities as biological organisms, in terms of quantitative relations for human organizations.

The most fundamental quantity characterizing any physical system is its energy, which in turn sets dynamical time scales. For many complex systems, particularly those in biology and society, energy consumption is the key to identify leading rhythms of internal organization, growth and information creation. For a biological organism energy consumption per unit time is a measure of its metabolism. Remarkably metabolic rates Y, scale with body size M (mass) according to a simple power relation:

$$Y = Y_0\, M^{\beta}, \ \beta = 3/4, \tag{7.1}$$

which holds across 21 orders of magnitude in body mass, and all different species (West et al., 1997, 1999). The exponent $\beta = 3/4$ can be understood in terms of the networks of resource distribution inside organisms (e.g., the vascular system of animals and plants). These networks are hierarchical; distributing resources from central points (e.g., heart) to every component of the system (e.g., cells). In this way, they carry a conserved fluid to every part of a volume of tissue that constitutes the organism. These networks have been optimized by natural selection to be efficient, in the sense of dissipating the least amount of energy possible. Under these conditions, the networks can be abstracted as hierarchical branching processes with a non-trivial fractal dimension. In d dimensions, it can be shown that the exponent $\beta = d/(d + 1)$, which becomes 3/4 for $d = 3$. Because the scaling law (7.1) has the dimension of a rate, it also predicts how characteristic times, characterizing the organism's behavior, scale with size. Specifically, characteristic times (e.g., lifespan) per unit mass scale as $M^{1/(d+1)}$, while rates (such as heart or respiratory rhythms) scale inversely to times, as $M^{-1/(d+1)}$ (West et al., 1997, 1999).

At least at the superficial qualitative level, cities can, likewise, be thought of in terms of idealized networks of distribution that supply people, households and institutions with water, power, etc., and remove unwanted byproducts. It is less clear, however, what quantity may play the role of scale. The most natural is population, but other units, such as households or firms, are conceivable. Below, we show that adopting population as a measure of size of a city does indeed produce clear scaling relations for many urban quantities.

Another issue that arises when translating expectations from biological scaling, is the dimensionality of the system. While the natural dimension of a city may be $d = 2$, dense cities can also show growth in height producing structures that may have $2 < d < 3$. One last point concerns the definition of city itself (see Chapter 6). Many studies in urban geography have struggled with creating good definitions of the spatial limits of a city. This is difficult to do in terms of population density or built up area, since these quantities vary continuously from the city core to the periphery (increasingly in the US, city cores show decreases in population density, which has been moving to lower suburban locations). Because we are primarily interested here in human social activity, we adopted a definition of city that, as much as possible, reflects its economic character as an integrated labor market, comprised of a city core and all surrounding areas where substantial fractions of the population work within the city limits. These are Metropolitan Statistical Areas (MSA) in the USA, Larger Urban Zones (LUZ) in the European Union and Urban Administrative Units (UAU) in China.

7.2.1 A Timeline of Urban Scaling Results in ISCOM

As we briefly discussed above, our initial investigation and pursuit of data was guided by the presentation by one of us (West) at the ISCOM meeting in Paris 2003, drawing the analogy between biological organisms and human social organizations as a working hypothesis towards building a scaling theory of cities.

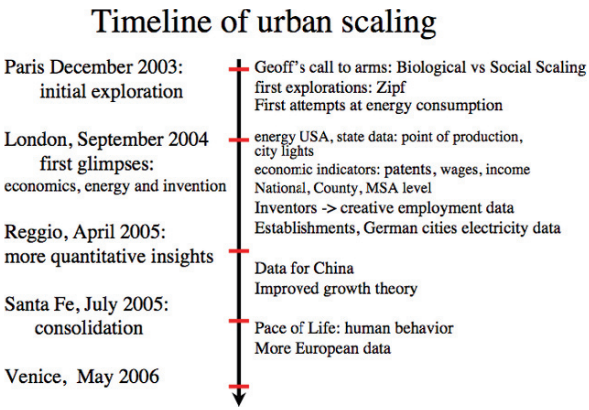

Fig. 7.1 Time line of our investigation in urban scaling. The initial motivation from Biology grew into a more complex and detailed picture as data came in. In retrospect, it is easy to recognize consecutive ISCOM meetings as major milestones in our progress

In the period between the ISCOM Paris meeting in December 2003 and the subsequent working group meeting in London in September 2004, our efforts concentrated on finding datasets to empirically test the expectations from Biological scaling for cities. A time line of our investigation in urban scaling is shown in Fig. 7.1. Energy consumption at the metropolitan level turned out to be difficult to measure in the USA, because most data are proprietary and fragmented. Information about points of production and about the networks of distribution is available but requires a large amount of reconstruction (and extrapolation) work to be mapped into city consumption patterns. We had more success with Germany (through our collaborators Dirk Helbing and Christian Kuehnert), where electrical production is tied in with individual cities for historical reasons. We also explored definitions of city, as it was unclear how best to aggregate socioeconomic data. We investigated scaling for counties, cities, and metropolitan areas. We found that, although indications of scaling existed at different aggregation levels, MSAs provided the most persuasive and consistent statistical signatures, and we adopted these units for subsequent studies in the USA and abroad. The rationale of the definition of MSAs, as the set definition of city that is as much as possible devoid of arbitrary administrative units and is instead an integrated economic and social unit, makes the most sense with our findings shown below. This does not preclude, of course, that even better definitions of city limits, an important problem in urban geography, can be defined. It is, in fact, plausible that greater understanding of urban functionalities, captured in a set of scaling relations to be discussed here, will aid guide such constructions.

7.2.2 Energy Consumption and Invention Rates vs. Urban Population Size

Our first results involved data on general socioeconomic activity, such as wages (Fig. 7.2), as well as on electrical energy consumption in German cities, see Table 7.1. Both data sets pointed immediately to fundamental differences in Biology, in that patterns of energy consumption and wealth generation did not show economies of scale ($\beta < 1$). In fact, if anything, these results indicated that scaling

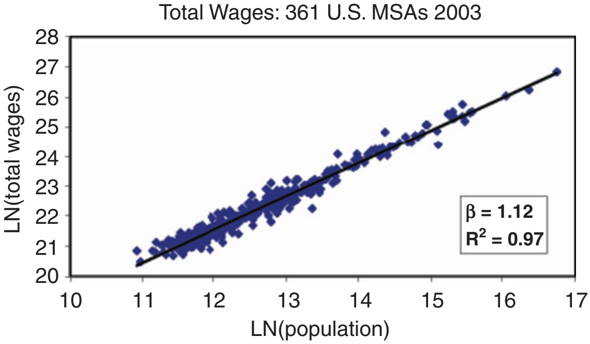

Fig. 7.2 Superlinear ($\beta = 1.12$) scaling of wages with metropolitan population for the USA in 2000

Table 7.1 Scaling exponents for electrical energy quantities for German cities in 2002

Variable	exponent ± standard deviation
Usable energy	1.09 ± 0.03
Household supply	1.00 ± 0.03
Length of cables	0.88 ± 0.03
Resistive losses	1.10 ± 0.03

is superlinear ($\beta > 1$), but that the effects were small, with $\beta \sim 1.1$–1.2, but statistically significant. We also found at this point – from Helbing et al. (Chapter 16 of this volume) – that certain amenities, such as numbers of restaurants, scaled with clear superlinear exponents, whereas others such as hospital beds, were approximately linear.

Although showing a mixed picture, these results pointed to several features that were confirmed by subsequent data. First, urban indicators, from infrastructure to socioeconomic characteristics, show clear and manifest scaling with city population size, characterized by exponents that deviate from unity by relatively small but statistically significant margins. Secondly, exponents for socio-economic quantities scale with $\beta > 1$, individual needs with $\beta \sim 1$, and material infrastructure (such as the length of electrical cables) scale with $\beta < 1$, see (Bettencourt, Lobo, Herbing, Kuehnert, & West, 2007).

7.2.3 Patenting Rates and Creative Employment

The next set of data we analyzed dealt with measures of innovation, as measured via patenting rates (Bettencourt et al., 2007). When organized in terms of inventor's residential address, new patents filed in the US can be tallied up by metropolitan statistical area. It has been recognized for quite some time that cities are the primary seats of innovation. Patenting, as an admittedly limited proxy to general innovative processes, has been studied in terms of its geographic preferential location for quite some time. As a result, patenting has been identified in the US and in other countries as a primary metropolitan phenomenon. Despite this rich evidence, the systematic study of the rate of patenting with metropolitan population had not been undertaken (Bettencourt et al., 2007).

The results of plotting new patents per MSA *vs*. MSA population size are shown in Fig. 7.3 for 1980 and 2000. Although there is some scatter in the data (which are shown without any averaging), a clear scaling trend is present in both years, with an exponent that is statistically consistent across two decades. This statistical invariance of the scaling exponent is particularly impressive when we note that, in those two decades, patenting subjects shifted dramatically away from traditional industries to new activities in electronics, software and biotechnology.

Patenting data also offered the possibility of testing several scenarios to explain the observed superlinear scaling of innovation rates with population. Two alternative scenarios are natural and testable given available data: observed increasing returns to scale (superlinear scaling) could (1) be the result of increased individual productivity, following from greater interactions with a larger number of inventors, proportional to city size; or, alternatively, follow from (2) individual productivity that is independent of city size, but is compensated by a greater number of inventors that are disproportionally represented the larger the city.

We further hypothesized that the first scenario, increased productivity due to greater interactions, should display a signature in patent co-authorship, since contact between a number of inventors naturally scale superlinearly (with an exponent $\beta = 2$, if all authors connect to each other). Thus, scenario (1) would predict a num-

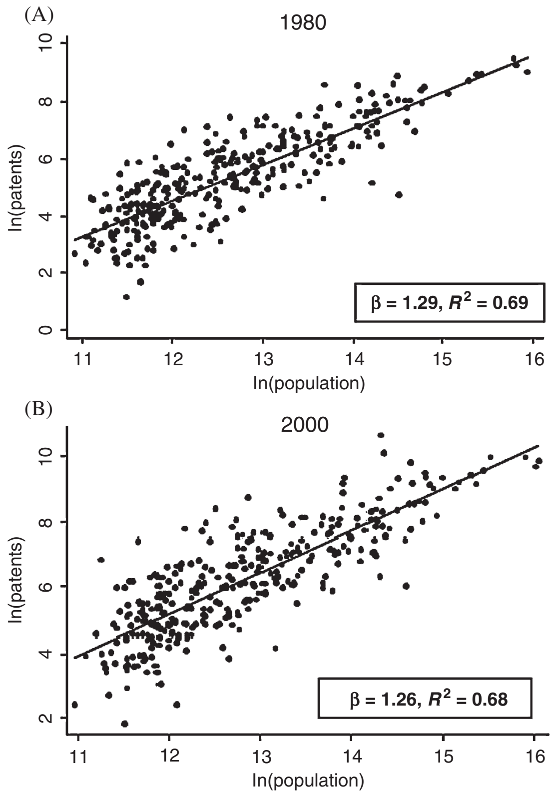

Fig. 7.3 Number of new patents per year in 1980 (**A**) and 2000 (**B**) vs. metropolitan population size. The solid line shows the result of a power law fit to the data with exponent β, shown as inset. Remarkably, despite enormous changes in technology, scaling laws stay statistically equivalent across the two decades, see (Bettencourt et al., 2007)

ber of inventors proportional to metropolitan population, but a superlinear scaling of inventor connectivity, which would yield the overall observed gains in productivity.

Conversely, scenario (2) predicted simply that productivity per inventor (average number of patents per author) would stay constant across city size, but that inventors would disproportionately be located in larger cities, thus accounting for greater rates of patenting. Table 7.2 and Fig. 7.4 show how empirical evidence settles the case in favor of scenario (2).

Table 7.2 Scaling of inventor connectivity, measured via patent co-authorship, and of number of inventors with metropolitan population size in the USA. These results, taken together with the evidence of Fig. 7.4, indicate that superlinear scaling in invention is primarily the result of the presence of a disproportionate number of inventors in larger cities and not due to superlinear increases in individual inventor productivity

Variable vs. # of	Scaling exponent
Connectivity	$\beta = 0.823 \pm 0.001$
Inventors	$\beta = 0.981 \pm 0.002$

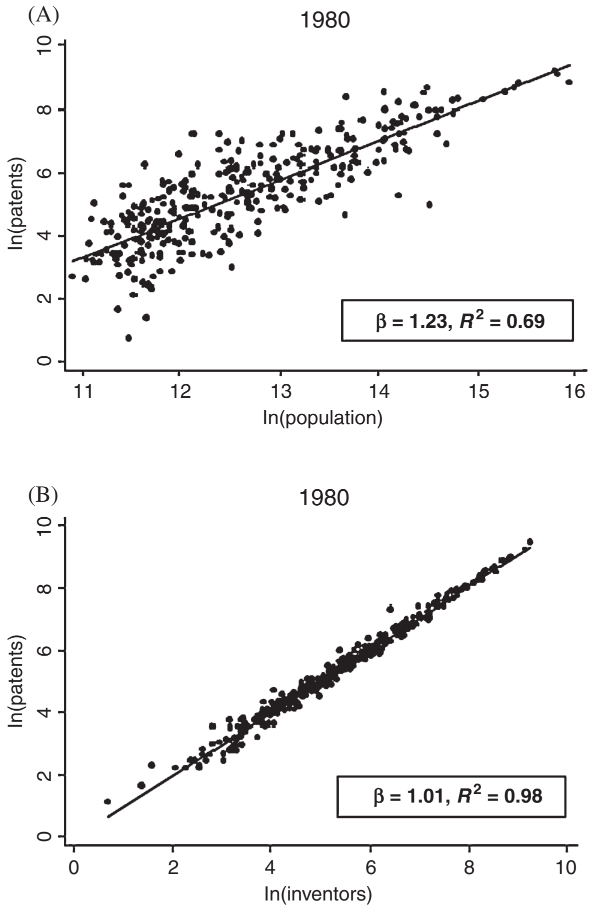

Fig. 7.4 Scaling of number of inventors with metropolitan population (**A**) and of patents with number of inventors (**B**). Taken together with the results of Table 7.2, these data indicate that inventors are disproportionately represented in the larger cities, but that individuals do not become more productive in larger populations

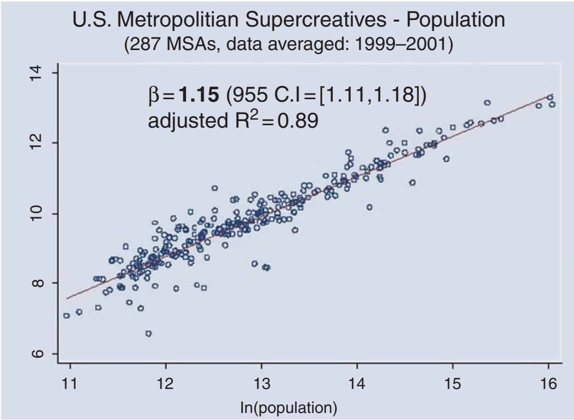

Fig. 7.5 Scaling of supercreative professionals with metropolitan city size

Finally, we asked whether the phenomenon observed here for inventors was in fact much more general, indicating a disproportionate number of inventive and creative activities the larger the city. Indeed, this expectation was confirmed by analyzing numbers of professionals in specific activities vs. city size, both in France and in the US (Chapter 8, this volume). As a summary, we show the scaling of numbers of "super-creative" professionals (Florida, 2004) with metropolitan population size (Bettencourt et al., 2007) in Fig. 7.5, indicating that scientific, technical, artistic, media and management activities scale superlinearly with city size, with an exponent $\beta = 1.15$. These results indicate that larger cities are not functionally scaled-up versions of smaller towns but, rather, are different in their relative activity breakdown, with more people disproportionately occupied in innovation and invention.

7.3 Urban Scaling and the Interplay Between Social Processes and Infrastructure

The set of results discussed above set the stage for a taxonomy of quantities that characterize cities as self-similar structures. Cities, in fact, realize both certain economies of scale in resource networks, typical of biology, and enable superlinear processes that are unique to human social organization.

7.4 Economies of Scale and Material Infrastructure

As we have already seen for electricity, certain aspects of infrastructure benefit from higher population density to realize economies of scale (see Table 7.3). Note that most of these quantities (length of cables, road surface) refer to material infrastructure networks, but not to resource consumption rates, which may scale superlinearly. Note also that the expectation for 1/3 power laws for infrastructure networks in a

Table 7.3 Scaling of infrastructural quantities with city size realizes economies of scale, analogous to those in Biology. These economies of scale appear as sublinear scaling ($b < 1$) laws

Y	β	95% CI	adj.- R^2	Observations	Country/year
Gasoline Stations	0.77	[0.74,0.81]	0.93	318	USA/2001
Gasoline Sales	0.79	[0.73,0.80]	0.94	318	USA/2002
Length of electrical cables	0.88	[0.82,0.94]	0.82	387	Germany/2001
Road surface	0.83	[0.74,0.92]	0.87	29	Germany/2001

2-dimensional city is not borne out by data. This may be a consequence of several factors, including gradients in population density, the not purely two dimensional character of cities, and the fact that resource delivery requirements may drive these networks to inefficiency.

This last point is important as it raises the question of cause and effect, namely whether infrastructure is the driver of human social behavior or if the converse is true. Although this question cannot be settled satisfactorily with the present evidence, the case of electrical consumption in German cities may be paradigmatic. Although economies of scale are certainly realized in cabling, total consumption scales superlinearly. This can only be achieved at the cost of rising inefficiency, which is manifested as a superlinear scaling in resistive losses (see Table 7.1). Thus, at least in this case, it is suggestive that human social needs drive infrastructure, rather than the other way around, as happens in biological organisms.

7.4.1 Individual Needs

Another interesting instance of urban scaling is that certain quantities are neither directly related to social behavior or to material infrastructure, but simply reflect individual needs that, once satisfied, cannot be easily expanded. For example, typically each person needs one job, one dwelling, and a typical amount of water and electricity at home. These quantities scale linearly with city size as shown in Table 7.4.

Note that although electrical consumption increased with city size, household consumption increases only linearly. Thus, it is the energy used to enable social

Table 7.4 Individual needs, such as household utility consumption, numbers of jobs, and dwellings, scale linearly with metropolitan population

Y	β	95% CI	adj. R^2	observations	Country/year
Total establishments	0.98	[0.95,1.02]	0.95	331	USA/2001
Total employment	1.01	[0.99,1.02]	0.98	331	USA/2001
Total household electrical Consumption	1.00	[0.94,1.06]	0.70	387	Germany/2001
Total Household electrical Consumption	1.05	[0.89,1.22]	0.91	295	China/2002
Total Household water Consumption	1.01	[0.89,1.11]	0.96	295	China/2002

productive activity – devoted to work rather than maintenance – ranging in scope from industry, to culture and learning, and street lighting that accounts for the superlinear character of the total consumption.

7.4.2 The Urban Economic Miracle

One of the most important characteristics of cities is that they are the primary centers for wealth creation in every human society. Although urban economists have established a positive relationship between urban size and productivity (Sveikauskas, 1975; Segal, 1976; Henderson, 2003) the identification of these statistical regularities in terms of scaling laws is new and extremely important for the understanding of the self-similar social processes that enable prosperity and economic growth. Measures of wealth creation or productivity follow exquisite superlinear scaling relation, across time and for different nations, with adjusted R^2 very close to unity, see Table 7.5, indicating nearly perfect fits.

Table 7.5 Wealth creation and productivity follow exquisite scaling laws with metropolitan population, with exponents b $\sim$ 1.10–1.15, and adjusted R^2 close to unity. Data aggregated at the level of the European Union encompasses several loosely connected urban systems and gives a poorer fit

Y	β	95% CI	adj.– R^2	observations	Country/year
Total Wages/yr	1.12	[1.09,1.13]	0.96	361	USA/2002
GDP/yr	1.15	[1.06,1.23]	0.96	295	China/2002
GDP/yr	1.13	[1.03,1.23]	0.94	37	Germany/2003
GDP/yr	1.26	[1.03,1.46]	0.64	196	EU/2003

Clearly, economic growth is strongly correlated to innovation and fast adaptation to new opportunities (Romer, 1986, 1990; Lucas, 1988, Glaeser, Kolko, & Saiz, 2001). Table 7.6 shows a summary of measures of innovation and employment in creative activities, which all show strong superlinear scaling.

Table 7.6 Superlinear scaling exponents for innovation and employment in innovative sectors

Y	β	95% CI	adj. R^2	observations	Country/year
New Patents/yr	1.27	[1.25,1.29]	0.72	331	USA/2001
Inventors/yr	1.25	[1.22,1.27]	0.76	331	USA/2001
Private R & D employment	1.34	[1.29,1.39]	0.92	266	USA/2002
"Supercreative" professionals	1.15	[1.11,1.18]	0.89	287	USA/2003
R & D employment	1.67	[1.54,1.80]	0.64	354	France/1999*
R & D employment	1.26	[1.18,1.43]	0.93	295	China/2002

7.4.3 The Darker Side of Cities: Costs, Crime and Disease

If the possibility of a larger and richer set of human contacts, made possible in a larger city, enables the creation of ideas and wealth, then they may also encourage

Table 7.7 Costs, the incidence of certain transmissible diseases, crime and other patterns of human behavior, such as walking speed (Bornstein & Bornstein, 1976), are also superlinear scaling laws with city size

Y	β	95% CI	Adj. R^2	Observations	Country/year
Cost of housing (per capita)	0.09	[0.07,1.27]	0.21	240	USA/2003
New AIDS cases	1.23	[1.18,1.29]	0.76	93	USA/2002
Violent crime	1.16	[1.11,1.18]	0.89	287	USA/2003
Walking Speed (per capita)	0.09	[0.07,0.11]	0.79	21	Several/1979

other types of less benign social activities (Milgram, 1970) such as those involved in crime (Glaeser & Sacerdote, 1999) and disease transmission. Thus, we may expect, at least in the absence of strong intervention, that crime and disease incidence (both temporal rates, analogous to idea or wealth creation) also scale superlinearly with city size. These expectations are well borne out by data as shown in Table 7.7, and Fig. 7.6.

These results highlight an important feature of scaling laws for quantities that are time dependent. Rates of per capita behavior scale with $N^{\beta-1}$, thus, under

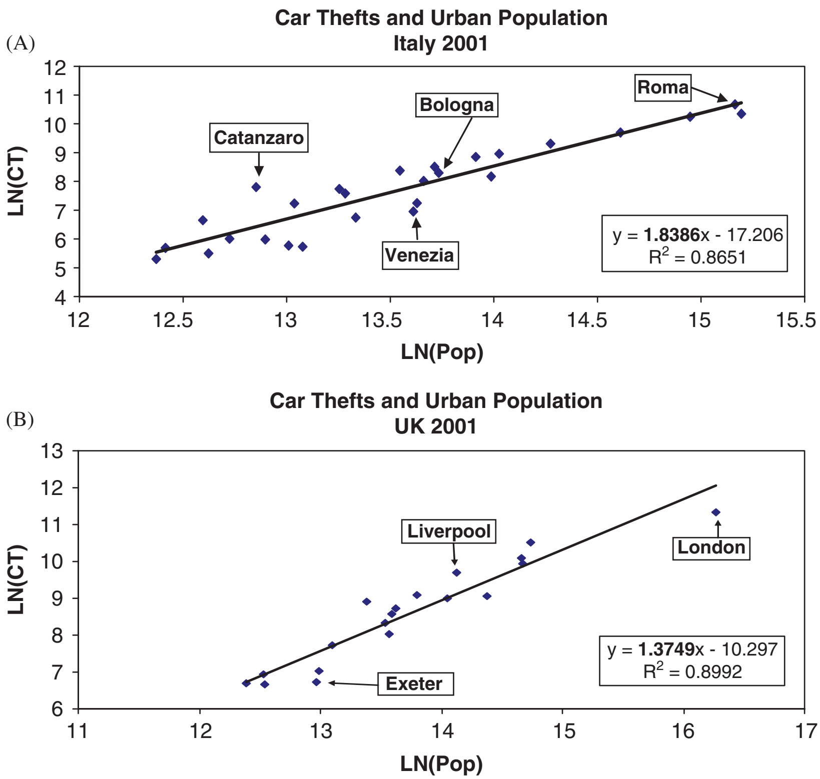

Fig. 7.6 Car thefts (per year) in Italian (**A**) and British (**B**) cities show superlinear scaling with metropolitan size. Cities above the scaling law are more theft prone than expected for their size

superlinear scaling, contrary to biology, the pace of social life (measured in disease incidence crime or indeed walking speed (Bornstein & Bornstein, 1976) increases with city size. Life is indeed faster in the big city.

7.5 Implications of Urban Scaling for Growth and Development

Growth is constrained by the availability of resources and their rates of consumption. Resources, Y, are utilized for both maintenance and growth. If, on average, it requires a quantity R per unit time to maintain an individual, and a quantity E to add a new one to the population, then this is expressed as

$$Y = R\,N + E\,(dN/dt), \tag{7.2}$$

where *dN/dt* is the population growth rate. This leads to the general growth equation:

$$\frac{dN\quad(t)}{dt} = \frac{Y_0}{E}\quad N(t)^{\beta} - \frac{R}{E}\quad N(t). \tag{7.3}$$

Its generic structure captures the essential features contributing to growth. Although additional contributions can be made explicit, they can typically be incorporated by a suitable interpretation of the parameters Y_0, R and E, leaving the general form of the equation unchanged. For simplicity, we assume that R and E are approximate constants, independent of N. The solution of (7.3) is given by

$$N(t) = \left[\frac{Y_0}{R} + \left(N^{1-\beta}(0) - \frac{Y_0}{R}\right)\exp[-\frac{R}{E}(1-\beta)t]\right]^{\frac{1}{1-\beta}} \tag{7.4}$$

This equation exhibits strikingly different behaviors depending on whether $\beta < 1, > 1$ or $= 1$. When $\beta = 1$, the solution reduces to classic exponential growth:

$$N(t) = N(0)e^{(Y_0-R)t/E}, \tag{7.5}$$

as shown in Fig. 7.7B, while for $\beta < 1$ it leads to a sigmoidal growth curve in which growth ceases at large times ($dN/dt = 0$), where the population approaches a finite carrying capacity given by

$$N(\infty) = (Y_0/R)^{1/(1-\beta)}, \tag{7.6}$$

as shown in Fig. 7.7A. This is characteristic of biological systems where the predictions of (7.3) are in excellent agreement with data. Thus, cities driven by economies of scale are destined to eventually stop growing.

The character of the solution changes dramatically when $\beta > 1$. If $N(0) < (R/Y_0)^{1/(b-1)}$, then (7.3) leads to unbounded growth for $N(t)$ (Fig. 7.7C). Growth becomes faster than exponential eventually leading to an *infinite* population in a *finite* amount of time given by

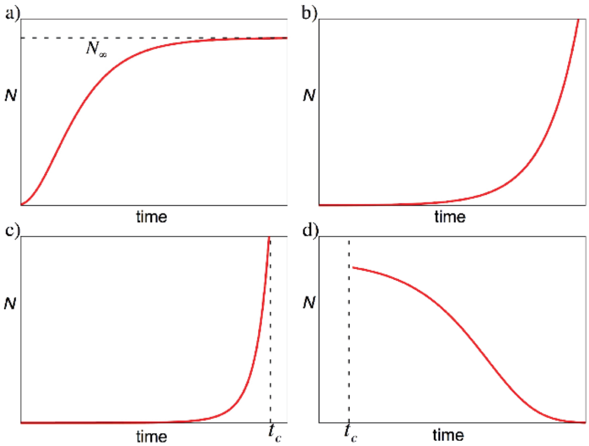

Fig. 7.7 Regimes of urban growth. Plots of size, N, vs. time t: (**A**) Growth driven by sublinear scaling eventually converges to the carrying capacity N_∞. (**B**) Growth driven by linear scaling is exponential. (**C**) Growth driven by superlinear scaling diverges within a finite time t_c (*dashed vertical line*) (**D**) Collapse characterizes superlinear dynamics when resources are scarce

$$t_c = -\frac{E}{(\beta-1)R} \ln\left[1 - \frac{R}{Y_0} N^{1-\beta}(0)\right] \approx \left[\frac{E}{(\beta-1)R}\right] \frac{1}{N^{\beta-1}(0)}. \tag{7.7}$$

For a city of about a million, t_c is in the order of a few decades. These results highlight an important characteristic of our social mechanisms to generate innovation and wealth. Even as we strive to accelerate prosperity and creativity, we sow the seeds for a crisis, manifested by a finite time singularity, where adaptation processes in society will break down. These crises can be avoided if major adaptations reset the dynamics to generate successive cycles of superlinearly driven growth as shown in Fig. 7.8. These expectations are borne out by data on the population growth of New York City or for the entire world population (Kremer, 1993; Cohen, 1995; Kurzweil, 2005).

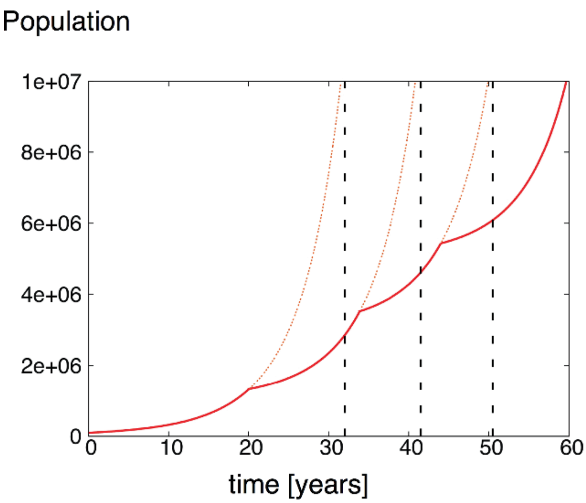

Fig. 7.8 Successive cycles of superlinear innovation reset the singularity and postpone instability and subsequent collapse. The *vertical dash lines* indicate the location of the sequence of potential singularities. Equation (7.7), with populations of the order of a million, predicts t_c in decades

7.6 Summary and Discussion

We have shown that power law scaling is a pervasive property of human social organization and dynamics in cities and holds across time and for different nations with very different levels of development, economic sector distribution, and with different cultural norms and geographic location. The existence of scaling laws signifies that cities within the same urban system (usually a nation) are self-similar. This is an extraordinary assertion indicating that, on average, different cities are scaled up versions of each other, particularly in terms of rhythms of social activity – such the creation of wealth and ideas, infectious contacts and crime, and patterns of human behavior – even if individual cities vary enormously in terms of their population constitution (e.g., age, race, ethnicity), geographic characteristics and countless other factors.

Urban scaling reveals a tension between quantities that constitute material infrastructure (length of cabling, road surface, etc.) and those that are eminently social (wealth, idea creation, etc.). Larger population densities allow for economies of scale in terms of infrastructure, but these may be driven to less than optimal operation by the requirements of social activity. A theory that encapsulates these compromises and is predictive of scaling exponents is a central objective for future research.

Particularly important are the consequences for growth of urban resource availability driven by innovation ($\beta > 1$) or economies of scale ($\beta < 1$), see summary in Table 7.8. The latter implies growth that eventually slows down, and an ultimate limit to the size of a city, in analogy to growth in biological organisms. The former is radically different, and probably unique to human social organization. It implies accelerating growth, towards a finite time singularity, thus linking inextricably the desired properties of fast economic and technological development to crises of adaptation. Growth in the superlinear regime never converges to a static equilibrium, defying common theoretical assumptions in economics. Instead, it requires constant adaptation to complex new situations created by faster and more efficient human social contact, both desirable and pathological. In particular, major adaptations must occur to reset growth under superlinear scaling to manageable levels, possibly explaining the cyclic nature of most instances of population and economic growth, as well as of technological development.

In closing, we would like to stress in this volume, in the spirit of the contribution by Sander van der Leeuw and collaborators, that cities can be seen as very

Table 7.8 Classification of scaling exponents for urban properties and implications for growth

Scaling Exponent	Driving Force	Organization	Growth
$\beta < 1$	Optimization, Efficiency	Biological	Sigmoidal, Long term stagnation
$\beta > 1$	Creation of Information, Wealth and Resources	Sociological	Boom/Collapse, Finite time singularity, Increasing acceleration/discontinuities
$\beta = 1$	Individual Maintenance	Individual	Exponential

large-scale social information engines, producing open ended innovation and wealth (as well as waste and pollution) out of incoming population, energy, and other resources. As cities grow, disproportionately large numbers of their parts – in terms of population and institutions – are dedicated to innovation, forcing their population either into cycling out of the city or towards adaptation to new roles and behaviors. It is perhaps this necessity for the city as the engine of human social development that makes *man a political animal by nature*. It may well be that the self-similarity revealed by urban scaling laws is the clearest quantitative expression of our unique human social nature, and its understanding the key to a future where sustainability and creativity can coexist.

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