The Size, Scale, and Shape of Cities

Article *in* Science · March 2008

DOI: 10.1126/science.1151419 · Source: PubMed

1 author:

Michael Batty
University College London

Science
AAAS

The Size, Scale, and Shape of Cities

Michael Batty, *et al.*

Science **319**, 769 (2008);
DOI: 10.1126/science.1151419

12. United Nations Human Settlements Programme (UN-HABITAT), "Global urban observatory, urban indicators programme, phase III" (UN-HABITAT, New York, 2005).
13. United Nations Population Fund and the Population Reference Bureau, "Country profiles for population and reproductive health: policy developments and indicators" (UNFPA and the Population Reference Bureau, New York, 2005).
14. M. Garenne, in *Africa on the Move: African Migration in Comparative Perspective* M. Tienda, Ed. (Wits Univ. Press, Johannesburg, South Africa, 2006) pp. 252–279.
15. United Nations Population Division, "World urbanization prospects: the 2005 revision population database" (United Nations Population Division, New York, 2006).
16. World Bank, "World development indicators" (World Bank, Washington, DC, 2007).
17. C. Stephens, *Environ. Urban.* **8**, 9 (1996).
18. S. Yusuf, K. Nabeshima, W. Ha, *J. Urban Health* **84**, 35 (2007).
19. A. Wagstaff, "Inequalities in health in developing countries: swimming against the tide?" (World Bank, Washington, DC, 2002).
20. Measure Demographic and Health Surveys, (Measure DHS, 25 July 2007); www.measuredhs.com/.
21. D. Gwatkin, K. Johnson, A. Adam Wagstaff, S. Rutstein, R. Pande, "PovertyNet Library: socio-economic differences in health, nutrition, and population" (World Bank, Washington, DC, 2007); http://poverty2.forumone.com/library/view/15080.
22. African Population and Health Research Center (APHRC), "Population and health dynamics in Nairobi's informal settlements" (African Population and Health Research Center, 2002).
23. I. M. Timaeus, L. Lush, *Health Transit. Rev.* **5**, 163 (1995).
24. B. M. Popkin, *Am. J. Clin. Nutr.* **84**, 289 (2006).
25. D. M. Mannino, S. A. Buis, *Lancet* **370**, 765 (2007).
26. World Health Organization, "World report on road traffic injury prevention" (World Health Organization, Geneva, Switzerland, 2004).
27. S. I. Hay, C. A. Guerra, A. J. Tatem, P. M. Atkinson, R. W. Snow, *Nat. Rev. Microbiol.* **3**, 81 (2005).
28. UNAIDS, Joint United Nations Programme on HIV/AIDS, "Report on the global AIDS epidemic" (UNAIDS, New York, 2006).
29. V. K. Chadha, P. Kumar, P. S. Jagannatha, P. S. Vaidyanathan, K. P. Unnikrishnan, *Int. J. Tuberc. Lung Dis.* **9**, 116 (2005).
30. Knowledge Network on Urban Settings, World Health Organization Commission on Social Determinants of Health, "Our cities, our health, our future: acting on social determinants for health equity in urban settings" (World Health Organization Kobe Centre, Japan, 2007); www.who.or.jp/knusp/knus.html.
31. J. Reader, *Cities* (William Heinemann, London, 2004).
32. I thank D. Gwatkin, E. Rehfuess, B. Williams, A. Bierrenbach, and K. Lonnroth for helpful comments on the manuscript.

10.1126/science.1150198

PERSPECTIVE

The Size, Scale, and Shape of Cities

Michael Batty

Despite a century of effort, our understanding of how cities evolve is still woefully inadequate. Recent research, however, suggests that cities are complex systems that mainly grow from the bottom up, their size and shape following well-defined scaling laws that result from intense competition for space. An integrated theory of how cities evolve, linking urban economics and transportation behavior to developments in network science, allometric growth, and fractal geometry, is being slowly developed. This science provides new insights into the resource limits facing cities in terms of the meaning of density, compactness, and sprawl, and related questions of sustainability. It has the potential to enrich current approaches to city planning and replace traditional top-down strategies with realistic city plans that benefit all city dwellers.

Throughout the 19th century, social commentators universally damned the growth of cities, the chorus rising to a crescendo in the writings of William Morris, who spoke of "the hell of London and Manchester" and "the wretched suburbs that sprawl all round our fairest and most ancient cities" (*1*). These sentiments have dominated our approach to cities and their planning to this day: Cities are still seen as manifesting a disorder and chaos requiring control through the imposition of idealized geometric plans. There have been few dissenting voices, an exception being Jane Jacobs (*2*), who argued half a century ago that far from being homogeneous and soulless, cities are essential crucibles for innovation, tolerance, diversity, novelty, surprise, and most of all, for economic prosperity.

In the past 25 years, our understanding of cities has slowly begun to reflect Jacobs's message. Cities are no longer regarded as being disordered systems. Beneath the apparent chaos and diversity of physical form, there is strong order and a pattern that emerges from the myriad of decisions and processes required for a city to develop and expand physically (*3*). Cities are the example par excellence of complex systems: emergent, far from equilibrium, requiring enormous energies to maintain themselves, displaying patterns of inequality spawned through agglomeration and intense competition for space, and saturated flow systems that use capacity in what appear to be barely sustainable but paradoxically resilient networks.

Centre for Advanced Spatial Analysis, University College London, 1-19 Torrington Place, London WC1E 6BT, UK. E-mail: m.batty@ucl.ac.uk

The Size and Scale of Cities

Urban complexity has its basis in the regular ordering of size and shape across many spatial scales (*4*). Cities grow larger to facilitate a division of labor that generates scale economies (*5*), and it is a simple consequence of competition and limits on resources that there are far fewer large cities than small. However, the self-similarity observed across many spatial levels implies that the processes that drive agglomeration and clustering in small cities are similar to those in large cities; indeed in cities of any size.

A lot of the work on scaling has taken cities, firm sizes, and incomes as key exemplars. In the 1930s, Christaller first showed that market areas or hinterlands around cities scaled across a geometric hierarchy in terms of their population size (*6*). Gibrat (*7*) argued that such scaling could be approximated from log-normal distributions, which emerge when objects (cities and firms) grow randomly but proportionately, whereas Simon's simple birth and death models (*8*) have been widely applied to demonstrate the same logic. Recently Gabaix, Solomon, and others (*9*, *10*) have shown that such growth generates scaling in the steady state, which is consistent with various economic models that explain how systems grow through agglomeration. A consequence of all this is that many physical (geometric) and functional (economic) explanations are converging (*11*, *12*). The volume of work is now so extensive that a wide variety of size distributions are now known to show scaling (*13*). Examples for city populations over 1 million, for cities in the United States with over 100,000 people, and for the 200 tallest buildings in the world are shown in Fig. 1A.

There are still many puzzles associated with such scaling. Gibrat's law assumes that not only are growth rates random but so is their variance, yet there is now considerable evidence that such rates and their variances scale with size (*14*, *15*). Despite agglomeration effects that relate to size, there is a strong suspicion that the best places to locate new growth are in smaller rather than larger cities, reflecting the tradeoff between economies of scale and congestion, which both increase as cities get bigger. The implications are controversial. The age-old question of what the "optimal" size for a city is is as open as it has ever been.

Interactions, Networks, and Densities

Where the focus is on interactions between cities in terms of trade or migration, and within cities in terms of commuting, shopping, and other social movements, scaling has recently been discovered with respect to such networks. In the past, the focus was almost entirely on modeling traffic flows rather than on the properties of such networks per se (*16*), although the distribution of traffic volumes originating from or destined for different locations in a city has long been known to be scaling (Fig. 1B). Density distributions are also essential outcomes from urban economic models where the focus is on the tradeoff between travel cost or distance and the cost of space, as in rent, house prices, and land values (*17*). These distributions generate an approximate scaling against distance from an established center shown for London in Fig. 1C. As yet, there are no integrated theories tying these ideas together in an economic framework consistent with physical scaling, although progress is being made (*18*). Nor are there any serious uses of such theory to determine ways in which realistic city plans might be devised, although many land-use–transportation models that incorporate such ideas are being used to evaluate the feasibility of new urban plans (*19*). After 40 years of effort, their use is hardly routine but this is still progress.

With the growth of network science (*20*), the focus has been on physical infrastructures, such as the topology and geometry of street and rail systems. These systems are characterized by scale-free activity at the nodes as measured by their number of connections, for example, but it is now clear that this type of scaling is also reflected in traffic volumes at nodes as we imply in Fig. 1B. Much of the work in network science to date has been on classifying network topologies into various shapes of graphs through their statistical properties. Where it is being applied, it is being used to inform the way in which people and vehicular traffic move at quite fine spatial scales, such as in pedestrian densities and dynamics in street networks, which show similar scaling to city size (*21*, *22*). Because network science is not rooted primarily in Euclidean space but deals as much with topologies, such as social networks, this suggests ways in which our longstanding physical approach to cities can be consistently linked to urban economic and social functions that only obliquely manifest themselves in geographical or physical terms. Interesting and useful insights about connectivity and inequality that reflect new ideas about how close or how segregated and congested people are in cities are being discovered (*23*). All this is essential to understanding how information flows both replace and complement material flows of resources that have underpinned the spatial organization of cities hitherto.

Urban Geometry and Morphology

City morphology is reflected in a hierarchy of different subcenters or clusters across many scales, from the entire city to neighborhoods, organized around key economic functions. These in turn reflect the resources needed to service them and the spatial range over which their demand is sustainable. Cities are thus classic examples of fractals in that their form reflects a statistical self-similarity or hierarchy of clusters (*24*). Large cities often develop as existing towns coalesce, with new edge cities being developed on their periphery as they change in scale. The way such fractal growth occurs has been likened to various physical growth processes ranging from percolation to diffusion-limited aggregation (*25*). These map onto the more established notions of density decay with respect to distance in cities from their established center. A typical picture for greater London is shown in Fig. 2A.

Presenting this structure in terms of the transportation network in Fig. 2B provides another perspective on fractal structure consistent with scale-free networks. Allometric methods can be used to link the size and shape of living objects to the networks they use to deliver resources to their parts (*26*). West and his colleagues have recently shown that as cities grow in size, physical networks tend to grow more slowly than city size; that is, the physical infrastructure used to move resources around does not increase as fast as the number of such resources, whereas key economic activities such as the number of innovations as measured through financial services, patents, and scientific products increase faster than city size in terms of population (*27*). Thus, big cities appear more attractive to the most productive industries, but it is easier to move resources around in small cities.

Models that simulate fractal structures can be calibrated to real situations and used for future predictions based on simple rules of land development (*28*). But their most effective use is to deconstruct the rules that have been used in the past to design idealized cities (Fig. 2). A typical city plan from Renaissance Italy (Fig. 2C) is a stylized symmetric construction whose fractal structure is highly contrived but could be formally generated by tight rules being placed on the size and shape of development. Ebenezer Howard's "city of tomorrow" (*29*) (Fig. 2D) presented the geometric logic according to which many 20th-century new towns were designed, again implying strict rules of morphological placement with respect to the components that make the town function at different scales. When implemented, most of these idealizations rarely provide the quality of life for their inhabitants that such order anticipates. They are simply too naïve with respect to the workings of the development process, the competition for the use of space that characterizes the contemporary city, and

Fig. 1. Scaling in cities. (**A**) City and building size distributions. (**B**) Rank-size scaling in London. (**C**) Density scaling in London. In (A) and (B), vertical axes are populations in rank order from largest to smallest, $P(r)$, normalized by their mean values $<P(r)>$, and horizontal axes are ranks r normalized by their mean values $<r>$. In (C), the vertical axis is population density ρ_j at place j with the horizontal axis, d_j, being distance to j from the center of the metropolis.

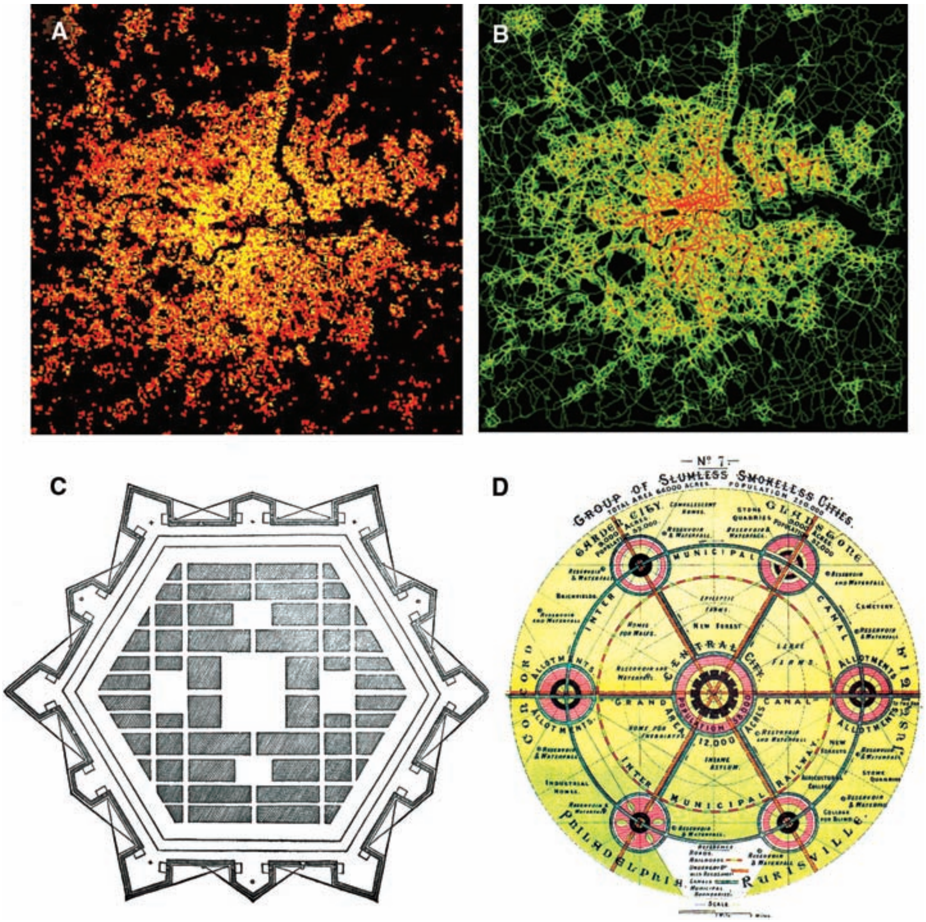

Fig. 2. Fractal cities. (**A**) Population morphology of London. (**B**) The road network in London colored by level of connectivity. (**C**) An idealized geometric city. (**D**) Howard's garden city of tomorrow (*29*).

the degree of diversity and heterogeneity that the most vibrant cities manifest.

A New Science for City Planning?

In the study of cities, there are many competing paradigms. This science has the potential not only to join some of these together but also to improve theories to the point where city planners can develop operational tools grounded in extensive empirical data. In terms of size and scale, we do not yet have a clear view of how big a city is in terms of the density of its activities, the volume of its built and natural space, and the way in which materials, information, and people interact to sustain such forms. We cannot have a clear view of what density means, what energies and costs are incurred by different urban geometries, and how feasible policies are for increasing compactness and managing sprawl until we have good answers to these questions.

The science advocated here has the potential to address these questions. As cities grow in size, they change in shape through allometry and this changes the energy balance used to sustain them. What we are currently learning is that different sizes and shapes of cities imply different geographical advantages, and this again casts doubt on the question of what the ideal size of city should be. Network science provides a way of linking size to the network forms that enable cities to function in different ways. How materials are processed, their resulting waste products and pollution, and their multiplier effects on other urban activities can be tracked using the network dynamics that is implicit in this science, whereas the speed at which change can be initiated through networks provides essential insights into the potential effectiveness or otherwise of different urban policies. The impacts of climate change, the quest for better economic performance, and the seemingly intractable problems of ethnic segregation and deprivation due to failures in job and housing markets can all be informed by a science that links size to scale and shape through information, material, and social networks that constitute the essential functioning of cities.

We have only just started in earnest to build theories of how cities function as complex systems. We do know, however, that idealized geometric plans produced without any regard to urban functioning are not likely to resolve any of our current urban ills, and this new physics makes us much more aware of the limits of planning. It is likely to lead to a view that as we learn more about the functioning of such complex systems, we will interfere less but in more appropriate ways (*30*). Changes that we propose are then likely to be much more effective in resolving problems than the ways in which city planning has operated in the past. The challenge is to aggressively enrich this science and move it to the point where it can be successfully used to plan better cities. We are but at the beginning.

References and Notes

1. W. Morris, *Architecture, Industry and Wealth: Collected Papers* (Longmans, Green, and Co., London, 1902).
2. J. Jacobs, *The Death and Life of Great American Cities* (Random House, New York, 1961).
3. M. Batty, *Cities and Complexity: Understanding Cities Through Cellular Automata, Agent-Based Models, and Fractals* (MIT Press, Cambridge, MA, 2005).
4. V. Pareto, *Cours d'Economie Politique* (Droz, Geneva, Switzerland, 1896).
5. G. K. Zipf, *Human Behavior and the Principle of Least Effort* (Addison-Wesley, Cambridge, MA, 1949).
6. W. Christaller, *Die Zentralen Orte in Suddeutschland* (Gustav Fischer, Jena, Germany, 1933).
7. R. Gibrat, *Les Inégalités Économiques* (Librarie du Recueil Sirey, Paris, 1931).
8. H. A. Simon, *Biometrika* **42**, 425 (1955).
9. X. Gabaix, *Q. J. Econ.* **114**, 739 (1999).
10. A. Blank, S. Solomon, *Physica A* **287**, 279 (2000).
11. G. Duranton, *Am. Econ. Rev.* **97**, 197 (2007).
12. J. Eeckhout, *Am. Econ. Rev.* **94**, 1429 (2004).
13. A. Clauset, C. Rohilla Shalizi, M. Newman, preprint available at http://arxiv.org/abs/0706.1062v1 (2007).
14. M. H. R. Stanley *et al.*, *Nature* **379**, 804 (1996).
15. M. Batty, *Nature* **444**, 592 (2006).
16. A, G. Wilson, *Entropy in Urban and Regional Modelling* (Pion Press, London, 1970).
17. C. Clarke, *J. R. Stat. Soc. Ser. A* **114**, 490 (1951).
18. M. A. Fujita, A. Venables, P. Krugman, *The Spatial Economy: Cities, Regions and International Trade* (MIT Press, Cambridge, MA, 1999).
19. M. Wegener, in *GIS, Spatial Analysis, and Modeling,* D. J. Maguire, M. Batty, M. F. Goodchild, Eds. (ESRI Press, Redlands, CA, 2005), pp. 203–220.
20. M. Newman, A. L. Barabasi, D. J. Watts, *The Structure and Dynamics of Networks* (Princeton Univ. Press, Princeton, NJ, 2005).
21. S. Scellato, A. Cardillo, V. Latora, S. Porta, *Eur. Phys. J. B* **50**, 221 (2006).
22. D. Helbing, L. Buzna, A. Johansson, T. Werner, *Transp. Sci.* **39**, 1 (2005).
23. G. Chowell, J. M. Hyman, S. Eubank, C. Castillo-Chavez, *Phys. Rev. E Stat. Nonlin. Soft Matter Phys.* **68**, 066102 (2003).
24. M. Batty, P. A. Longley, *Fractal Cities: A Geometry of Form and Function* (Academic Press, San Diego, CA, 1994).
25. H. A. Makse, S. Havlin, H. E. Stanley, *Nature* **377**, 608 (1995).
26. G. B. West, J. H. Brown, B. J. Enquist, *Science* **284**, 1677 (1999).
27. L. M. A. Bettencourt, J. Lobo, D. Helbing, C. Kühnert, G. B. West, *Proc. Natl. Acad. Sci. U.S.A.* **104**, 7301 (2007).
28. I. Benenson, P. M. Torrens, *Geosimulation: Automata-Based Modeling of Urban Phenomena* (Wiley, London, 2004).
29. E. Howard, *To-Morrow: A Peaceful Path to Real Reform* (Routledge, London, 1898; new ed. 2003).
30. P. W. Anderson, *Science* **177**, 393 (1972).

31. The author thanks S. Marshall and D. Smith of University College London for help with Figs. 2C and 2B, respectively.

10.1126/science.1151419