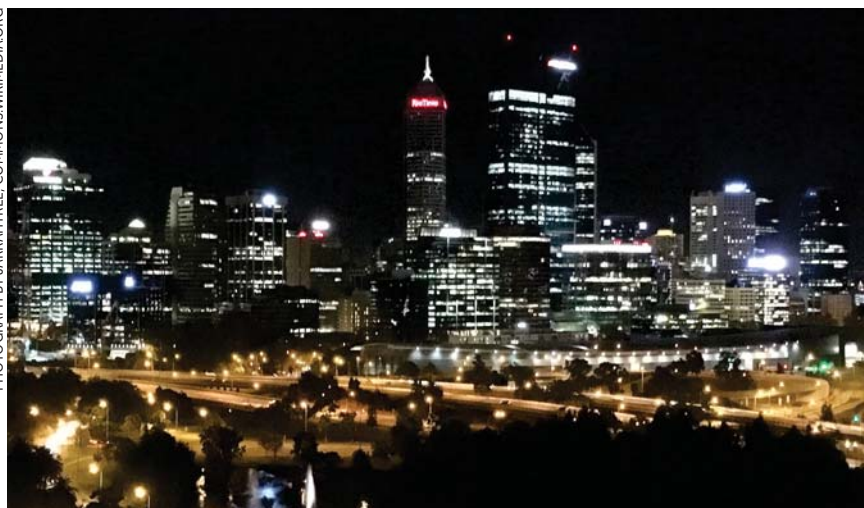


An intriguing take on complexity

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Complex systems such as living organisms, economies, companies, and cities span an enormous range of sizes. A tiny organism called mycoplasma has one of the smallest genomes of any free-living bacteria—just 580 070 base pairs long—and a mass on the order of 10^{-13} g. At the other extreme of the animal kingdom, a blue whale checks in with a mass of around 10^8 g. Data accumulated over the years show that several characteristics of organisms scale with system size. There are, of course, many exceptions to the rule, but the undeniable trends are astonishing. In *Scale: The Universal Laws of Growth, Innovation, Sustainability, and the Pace of Life in Organisms, Cities, Economies, and Companies*, Geoffrey West argues that in spite of their bewildering complexity, robust trends and patterns emerge for those and other systems.

Notable among those trends is the rate at which an organism consumes energy, or the metabolic rate, which scales approximately as the $\frac{1}{4}$ power of the organism's mass. West and his collaborators have in the past 20 years published an impressive slew of papers on metabolic rates. As he puts it in *Scale*, "Metabolism is the fire of life . . . and food, the fuel of life."

Following simple dimensional analysis, the characteristic time for many life processes scales as a $\frac{1}{4}$ power of the mass of the organism. Quarter-power scaling applies to, among other things, life span and heart rate; indeed, those attributes are interrelated. Many of West's observa-

tions have been made in earlier books, and the author includes many citations to useful previous literature.

Part of the energy taken in by an organism is used for its maintenance and is proportional to its size. The rest of the energy is available for its growth and reproduction. For a large enough organism, the maintenance cost would exceed the available metabolic energy, and thus growth would necessarily cease. Were the metabolic energy of an organism to scale superlinearly with size, the organism size would grow without limit.

In the second half of the book, West considers the scaling and long-term sustainability of companies, cities, and economies. We once again observe interrelated processes all described by power laws. West's key finding is that urban metrics such as GDP, patents, and crime all scale with population size, with an exponent of around 1.15. The message here is that both the good and the bad scale superlinearly with population in cities. Typically, key attributes of companies scale sub-linearly with size, in a manner between that of organisms and cities.

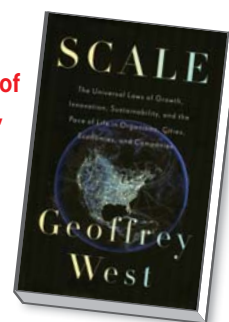
West links superlinear growth to a city's sustainability. He argues that power-law scaling with an exponent greater than 1 occurs because of positive feedback mechanisms driven by social interactions. The result is open-ended growth of a city's population. But West also invokes a groundbreaking 2001 paper by physicists Anders Johansen and Didier Sornette called "Finite-time singularity in the dynamics of the world

Scale

The Universal Laws of Growth, Innovation, Sustainability, and the Pace of Life in Organisms, Cities, Economies, and Companies

Geoffrey West

Penguin Press, 2017. \$30.00



population, economic and financial indices" to suggest that explosive growth of cities cannot be sustained without innovations—for example, printing, the telephone, electricity, and the smartphone—occurring at ever more rapid rates.

What underlies the quarter-power scaling for organisms is a topic of research with which both West and I are involved. West gives his take in a chapter titled "The Fourth Dimension of Life: Growth, Aging, and Death," which claims that fractal networks are responsible. He argues that an additional dimension arising from fractality "leads to organisms' functioning as if they are operating in four dimensions." The discussion is not convincing; several researchers, including me, have argued that quarter-power scaling can arise without underlying fractality. Unfortunately, West presents the story as if the case has been closed, which I fear may mislead readers.

West also does not address the fascinating question of how convergent evolution resulted in the coexistence of two dominant templates for life on Earth: animals that move, are powered by a heart, and have a surface area that scales as the $\frac{2}{3}$ power of their volume; and trees that are rooted organisms, do not have a pump, and whose surface area and number of leaves are proportional to the tree volume.

Despite those objections, *Scale* is a fun book to read and an inspiring celebration of complex systems. Perhaps West's most enduring contribution will be to stimulate scientists to think about the patterns around us and contemplate the simplicity underlying the complexity.

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