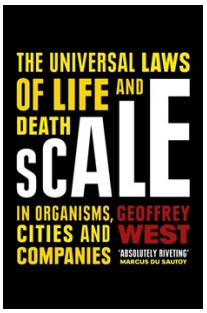
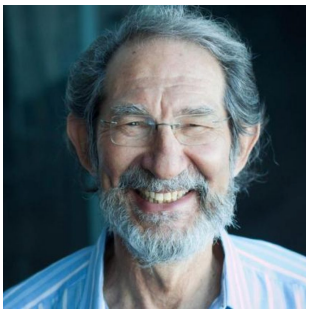
Scale by *Geoffrey West*. Weidenfeld & Nicolson, 2017, (496 p.) isbn 978-0-297-60947-6





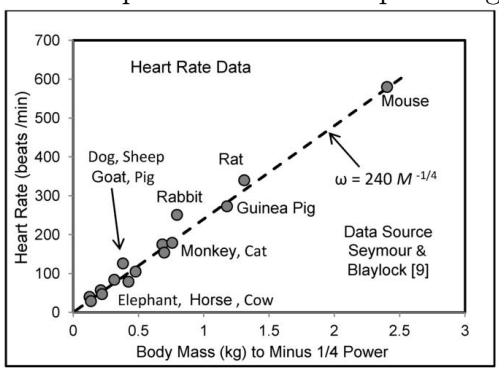
Geoffrey West

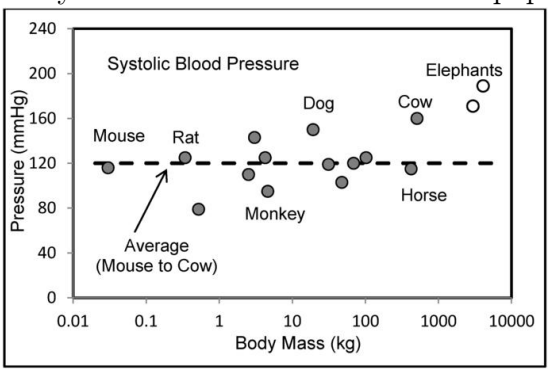
Geoffrey West is a theoretical physicist who had a research group at Los Alamos and Stanford, but he turned his mind on discovering mathematical laws behind biological data. His first paper on this subject appeared in *Science* in 1997. He joined the Santa Fe Institute, a nonprofit theoretical research institute founded in 1984 dedicated to the multidisciplinary study of the fundamental principles of complex adaptive systems. In the period 2005-2009 he was the president of the institute.

In this popular science book he summarizes the insights he gained about complex systems. It reduces all in essence to an exponential growth that he observed in these systems: in biology (mammals and plants), in sociology (cities), and economy (companies). The appetising questions that he formulates in the beginning are certainly catching the attention of a general reader: Why can we not live longer dan about 120 years while elephants and whales do? Why do we stop growing at some point? Why do mice grow more cancer tumors than we do, and why do elephants get almost none? Why do companies have a short life while cities can survive major debacles? etc.

He claims to answer them all and he repeatedly explains that all this is due to exponential relationships. Set on the x-axis the volume of an animal and on the y-axis its daily energy requirements to survive (metabolic rate), and you will see this is an exponential relation. Using a log scale on both axes, this will result in a straight line, and its slope will explain the economy of scaling up. If the relation were linear, then doubling the volume would require doubling the energy. However, it turns out that a bigger volume is more efficient to maintain because the energy required is only increasing with 75% if the volume is doubled. This is known as Kleiber's law (1932).

The reason for this economy is that the energy is brought to all the cells in the body via the oxygen in the blood that exchanges energy in the mitochondria on the surface of the vessels. Since the cells form a 3D body while the vessel surface is only 2D, one would expect a ratio of 2/3 and not the 75%. But the blood vessel system from the aorta to the fine capillarities forms a fractal tree that is space filling, and it has therefore a theoretical Hausdorff dimension 3, but of course in practice the number of bifurcation levels will be finite and thus the fractal dimension is between 2 and 3. Moreover evolution has arranged that when a blood vessel bifurcates in thinner blood vessels, then the sum of their cross sections is equal to the one before the bifurcation, so that in the end, there is no extra energy required to pump the blood into the final capillaries. Bringing all this together explains the factor 3/4. In this book West says that his arguments 'lead to organisms functioning as if they are operating in four dimensions', which I could not understand. West probably borrowed this idea from his past research in superstring theory. One should read his Science paper of 1997





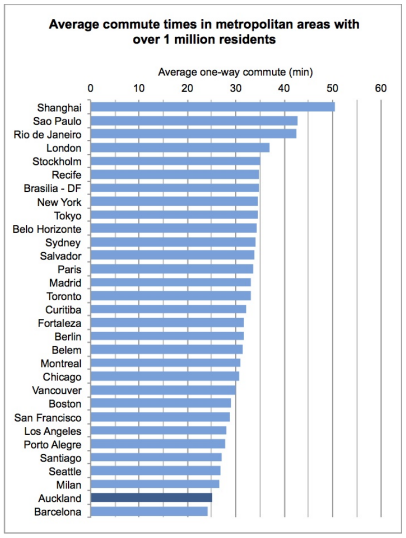
where he and his co-authors properly explain their model leading to this 3/4 ratio. Evolution has resulted in a systolic blood pressure that is approximately independent of body mass, which

imposes constraints on the cross section of aorta as well as capillarities.

Heat production (3/4) is directly related to metabolism and heart rate is slowed down (−1/4) because of the more efficient metabolism. The fact that the heart rate of an elephant is much less than that of a mouse means that an elephants lives longer because it lives much slower than a mouse. These, and many other parameters are all related to the above observation and thus all scale like a simple multiple of 1/4. Other examples are brain mass (3/4) and life span (1/4). At some point the energy that is brought to the cells are used to grow and some to repair, but in the end a majority goes to repairing until nothing is left for growing, which limits the length, and even more drastically leads to death in the end.

The discrepancy between a volume (3D) and the cross sections of a skeleton (2D) has led Galileo already much earlier to the conclusion that really giant Gozilla-like animals cannot exist because they would collapse under their own weight. There is an inherent mechanism that will prevent the development of giant mammals.

Everything said above about mammals can be repeated with proper rephrasing for trees and plants. These biological conclusions are rather well supported by data and are generally accepted. A large part of the book is however devoted to analogous arguments for cities and companies that not everybody agrees with. Correlation does not imply causality. For cities there is some urban metabolism in the form of physical input of pipes, wires, streets, railways,... to provide gas, electricity, water, food,... but there is also a socioeconomic component that scales like 1.15 and is thus growing much faster than 0.75. For that West counts the number of patents produced, amount of health care, height of salaries, productivity, but also the negative aspects like pollution, waste, crime, diseases,.. People in cities just live 15% faster than elsewhere. West attributes this remarkable scaling factor to the increase of multidisciplinarity in the highly connected social network that he measures for example by telephone communication.



There is natural limit to the size of a city which depends on the commuting time that people are willing to spend every day, which seems to be remarkably constant (about half an hour both ways). If larger, the city decomposes into somewhat independent enclaves, and become nodes in the larger global fractal socioeconomic network. The output of cities grows however at a super exponential rate, which requires proportional input while resources are finite and that inevitably leads to a catastrophic finite time singularity. This can only be avoided by innovation (we have known enlightenment, industrial revolution, and more recently the digital revolution). However these innovations need to come at an ever increasing speed. Hence the problem of sustainability to avoid the total collapse of the socioeconomic fabric. Time for a grand unifying theory of all possible disciplines and models from biology, sociology, environment, economy, technology,...

Finally for companies, the scaling rate is not 25% but only 10%. As they grow they work themselves more into a niche while diversity is precisely what is needed for innovation. So for companies, the behaviour is much like that of the biological systems, a decrease in growth and a finite life which West claims to be on average not more than about 10 years. This does not mean that the company goes bankrupt, bit it might have been merged into another one or split up in several subsidiary companies.

I think this is an interesting read. Mathematics are at a very low key though and West is repeating himself a bit too often to keep the reader focussed, but he makes it up with several interesting digressions and personal anecdotes.

Adhemar Bultheel