SUMMARY

SCALE

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Summary of “Scale” by Geoffrey West

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

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Introduction

One of the most complex and diverse phenomena in the universe is *life*. With more than eight million different species of organisms on the planet, species range from the smallest bacterium weighing less than a trillionth of a gram to the largest animal, the blue whale, which weighs up to a hundred million grams. Additionally, look at the tropical forests of Brazil which are home to hundreds of species of trees and millions of individual insects. Think about the differences between each of these species. Each one is conceived, born, and reproduced differently; they even die differently. Some bacteria live for an hour while whales can live for over a century! Even more, we have the incredibly complex and diverse social life of humans, who have brought cities, commerce, architecture, and a diversity of cultures to the planet. Compare this complexity with the simplicity and order of the planets orbiting the sun, or even the clockwork regularity of a watch or iPhone. Are there just a few simple rules that all organisms obey? Or is the evolutionary process arbitrary and random? As it turns out, the dynamics, growth, and organization of animals, plants, human social behavior, cities, and even companies are all subject to similar generic "laws" known as *scaling laws*.

Scaling laws allow us to view the major challenges in life from a different perspective and address a fascinating spectrum of questions, like: Why can we live for up to 120 years but not for a thousand or million? Why do mice, made of pretty much the same stuff we are, live for two to three years while elephants live for up to seventy-five? Why do we stop growing? To answer these questions and more, West explains how scaling laws govern relationships between various phenomena as they scale. To take a closer look at these laws and what we can learn about our world, then keep reading.

Scaling Laws Give Us an Inside Look At How the World Grows

Scaling refers to how an organism or system responds when its size changes. For instance, when an animal doubles in size or doubles its body weight, then its number of cells also doubles; however, its metabolic rate only increases by 75%, not 100% like you might expect. If you aren't sure what a metabolic rate is, it is the amount of energy an animal needs to stay alive. "Consider the following: elephants are roughly 10,000 times heavier than rats; consequently, they have roughly 10,000 times as many cells. The ¾ power scaling law says that, despite having 10,000 times as many cells to support, the metabolic rate of an elephant is only 1,000 times larger than a rat's." In other words, according to the scaling law, metabolic rates don't follow classic linear thinking. Instead, they only increase about 75 percent, representing 25 percent savings with every doubling of size.

In fact, if you plot a graph of the metabolic rate of animals against the body mass of those animals, you'll get a perfectly straight line. In other words, the metabolic rate of any animal - from a mouse to an elephant or blue whale - is perfectly fixed relative to its body mass. This scaling law for metabolic rate, or Kleiber's Law, is valid across almost all taxonomic groups, including mammals, birds, fish, crustacea, bacteria, plants, and cells. Similar scaling laws can also be applied to life-history events, including growth rate, heart rate, evolutionary rate, the height of trees, and more.

Remarkably, all mammals that have ever existed, including humans, are approximately scaled versions of a single idealized mammal. But did you know the same can be said for cities and companies? You may be thinking, "Is New York a scaled-up San Francisco, which is a scaled-up Boise, which is a scaled-up Santa Fe?" Sure, each city might look different and have its own history, geography, and culture, but data shows that population size and city infrastructure scale in the same way all across the globe. These scales indicate a systematic economy of scale with an exponent of 0.85

instead of 0.75. For example, no matter where you are in the world, fewer roads and electrical cables are needed per capita the bigger the city. Therefore, like organisms, cities are approximately scaled versions of one another despite their various differences in history, geography, and culture.

As if that wasn't enough, cities are also scaled socioeconomic versions of one another. Simply put, things like wages, wealth, patents, crime, and more, also scale with population size in a *superlinear* exponent of approximately 1.15. For example, when you record the number of patents registered in a city against its population, you'll see the number of patents increase 15 percent faster than the population. These scaling relationships are hardly a coincidence. Scaling laws show us how organisms and cities scale with size, allowing us to understand more clearly how the world grows. This also raises the question of, "Is the growth of the world sustainable?"

Why Godzilla or Superman Cannot Physically Exist

Science fiction introduces us to larger-than-life characters like Godzilla and Superman. But can they really exist? When Superman's incredible strength comes into question, we are provided with explanations like, "the ant can support weight hundreds of times its own" and "the grasshopper can leap the length equivalent to what man would consider several city blocks." While these explanations are certainly persuasive, they represent how humans misinterpret and make misleading conclusions drawn from correct facts.

As we've learned from the seventeenth-century Italian physicist and mathematician, Galileo Galilei, relative strength systematically increases as size decreases. So, if a small dog can carry two or three dogs of his own size on his back, then an ant can carry on his back a hundred ants of his size. And because we are 10 million times heavier than an average ant, then we are capable of carrying only about one other person on ours. In the end, ants have the correct strength appropriate for an insect their size, just as we do. Therefore, there is nothing extraordinary or surprising about an ant lifting one hundred times its own weight. This misconception arises from the fact that scaling doesn't follow a linear pattern.

Let's take a look at just one square foot. If you scale up the length of each side to three feet, then the enclosed area becomes nine square feet. While the sides increase by three times, the area inside increases by nine. Even more, the volume would increase 27 times! That's because area and volume do not scale linearly with length. Let's use this same logic to explain Godzilla. When you consider that Godzilla is about 60 times bigger than a human, his volume and mass would be 60^3, or 216,000 times the average weight of a human. But the length and strength of his bones would only increase by 60^2, or 36,000 times. The result? He would be 60 times heavier than the strength of his bones. In other words, his bones would snap under the weight.

Okay, so Superman and Godzilla aren't real. But this same logic can be applied to more practical scenarios too. For example, many people believed that the invention of the trans-Atlantic steamship wouldn't be economically viable because a ship purely powered by steam wouldn't be able to carry enough fuel for the trip and still have room for enough commercial cargo. English engineer Isambard Kingdom Brunel proved that it could be done by using a simple scaling argument. He recognized that the volume of cargo a ship could carry increases as the *cube* of its dimensions, while the strength of the drag forces increases proportionally to the size of the ship's hull, which is scaled by the *square* of the ship's dimensions.

Put more simply, a larger ship requires proportionately less fuel to transport each ton of cargo than a smaller ship. Bigger ships, therefore, are more energy-efficient and cost-effective than smaller ones.

Each Biological System Functions Using Three Fundamental Properties

As you already know, the scaling law explains the relationship between the metabolic rate and body mass of just about every animal. We have seen that metabolic rates scale with an exponent of ¾ but many other biological variables scale as multiples of ¼, like life span, length of aortas, and growth rate and heart rate. Furthermore, all biological systems function through networks such as the circulatory, respiratory and neural systems. Each one shares three generic properties; the first is that each of these systems fills a space, meaning that each tentacle of the network needs to reach every piece of the system they serve.

The second is that terminal units are invariant, meaning that endpoints, like the capillaries of the circulatory system, are the same size and have similar characteristics, no matter the size of the organism. In other words, the capillaries in a blue whale, the largest mammal on earth, are the same size as the smallest mammal, the shrew. You may find this surprising but think of it this way. Think about the electrical wiring in your home and the wiring in the Empire State Building. Your house is much smaller, but the wiring will be the same size. If the electrical outlets in the Empire State Building were scaled up relative to its height, then they would be ridiculously large, about 50 times larger than the ones in your home!

So while the size of the terminal units stays the same, the average distance between them differs. The distance can be scaled with body mass as a power law with an exponent of 1/12. A blue whale, for example, is a hundred million times heavier than a shrew; therefore, the average distance between capillaries is about 4.6 times larger. This law is why you won't see mammals bigger than the blue whale. Capillaries simply wouldn't be able to supply enough oxygen to the increasing number of cells, which would result in hypoxia of these cells, causing them to die.

This same logic can explain why there are no smaller mammals than the shrew. When it comes to the branching of vessels in the circulatory system, the aorta is our thickest vessel which branches into two thinner vessels, which then branch into two even thinner vessels, and so on until the terminal units are reached. The further the blood flows through the vessels, the slower it travels until it no longer pulsates and eventually flows like water in a pipe; these vessels are included in the nonpulsatile domain. All mammals have about 15 branchings in the nonpulsatile domain but the number of branchings in the pulsatile domain differs. Humans have about seven or eight branchings, a whale has 16-17, and a shrew has just one or two. If a mammal were to be any smaller, then the network wouldn't be able to support the blood flow in the nonpulsatile domain. It would be like the animal has a beating heart but no pulse!

Lastly, the third property of biological networks is that they become optimized, meaning that the energy used is the smallest it could possibly be given the design and network constraints. This is a result of the ongoing process of feedback and fine-tuning over time. For example, the human heart has now evolved to expend the least energy possible when pumping blood through the circulatory system.

The Fourth Dimension of the Biological Network

When you look at the mathematical details behind scaling laws, you'll find that most biological scaling factors include the numbers ¼ or ¾. The power in number four is perhaps derived in the properties of biological networks. To explain this, let's take a look at Lewis Richardson who once looked at data containing measurements of countries' borders and discovered he got different numbers from different datasets. This was because the measurements were taken at different resolutions; the higher the resolution, the longer the border became due to the amount of detail and clarity.

Benoit Mandelbrot then further developed this phenomenon by formally introducing the fractal dimensions based on the self-similarity of physical objects. In other words, the smoother the border line, the lower its fractal dimension. The more crinkly the border, the higher its fractal dimension and the longer it becomes each time it increases in resolution. This is the fourth dimension and might sound more confusing than it is. Consider a one-dimensional line on a two-dimensional piece of paper. The more crinkly the paper is, the more it fills the entire space of the page, therefore having a fractal dimension of 2. If an area is crinkly enough, it can behave like a volume, causing it to have a fractal dimension of 3. This additional dimension causes organisms to function as if they are operating in four dimensions.

In other words, biological networks are space-filling, which causes them to extend toward a dimension beyond their own. This fourth dimension explains why the number four is so important in scaling laws. This number even explains why humans stop growing in adulthood. For instance, if you double the size of an organism, you would also be doubling the number of cells it contains and the amount of energy it needs to survive. Scaling laws, however, instruct that the metabolic rate of an organism rises by factor 2 to the power of ¾. As a result, the demand for energy increases faster than energy can be produced, thus stopping growth altogether.

The Similarities Between Biological Networks and Cities

Just like with biological organisms, cities can also be thought of as networked systems. Biological organisms are similar in the way they scale up. As mentioned in chapter one, cities have several similarities in the way they scale up too. However, unlike biological organisms which are governed by the quarter-power exponents, urban systems are governed by the 0.85 and 1.15 exponents. You see, while a city might increase by 100 percent, the number of gas stations, the length of pipes, and the number of roads and wires will only increase by 85 percent.

This is due to the increased interactions and social lives of people living in big cities. Of course, this also means an increase in crime and disease scale with exponent 1.15. Because of these scaling laws, you can take the size of any city within a particular national urban system and predict with 80-90% accuracy its average wage, the number of patents produced, how long its roads are, how much crime was committed, how many restaurants there are, etc. These predictions, however, are dependent on a nation's economy, culture, and unique individualities of each nation.

The scaling of urban systems is also correlated with the scaling of social networks. For instance, over time, each person interacts with many other people and groups of people in the city, thus filling the available "socioeconomic space" and conforming to the space-filling property of scaling laws. As a result, social connectivity and socioeconomic quantities scale superlinearly with population size. So what exactly does this mean for modern life? Well, unlike biological organisms, in which a larger elephant metabolizes energy more *slowly* than a mouse and lives for a longer time, cities experience an *acceleration* as it increases in size.

For example, walking speed often increases as the size of the city increases. Small towns with a few thousand inhabitants average a walking speed that is just half that in a city of over a million people, where the average walking speed is a record four miles per hour. Furthermore, scaling laws can provide insight into the movement in cities. For instance, take a look at Park Street in Boston which averages 1,600 visits from people just 4 kilometers away once a month. With this information, we can predict how many people visit from 8 kilometers away with the same frequency of once a month, which is 400 people. By increasing by a factor 2, you can also predict that 64 people visit once a month from 20 kilometers away. Making such predictions surrounding the movement of cities is a powerful tool for planning urban development, such as the building of a new mall, football stadium, or even a future housing project.

As city size grows, social interaction and economic activity grow with it. For instance, larger cities will certainly contain more businesses, however, the diversity of those businesses - or the number of different types of establishments - increases incredibly slowly with size. For example, doubling the population of a city will result in a total number of businesses doubling as well; however, the increase in business diversity will be just five percent!

Scaling Reveals Just How Long Companies Stay in Business

Scaling isn't just limited to biological organisms and cities, scaling also occurs within businesses themselves. Things like sales, expenses, and profits all scale with size. Things like net income, gross profit, total assets, and sales all scale up as the company's size and the number of employees grow. So if a firm with 100 employees produces sales of $10 million, the same company would make $100 million in sales if it employed 1,000 people. Regardless of the industry, location, or age of the company, many patterns depend on the size of the business alone.

But what about the age of the company? Similar to living organisms, companies are born and grow. In most cases, they even die. Based on studies provided by S&P 500, the half-life of a company is around 10.5 years, meaning that 50% of all companies die after only 10.5 years. Few companies make it to 100 years - just 45 out of 1 million - and even fewer make it to 200 years - just one in 1 billion. Out of 28,853 companies that were on the US markets between 1950 and 2009, 78% died by 2009. Others were acquired by a merger with other companies, some went bankrupt or were liquidated, others privatized, etc.

If a company wants to achieve greater efficiency, many companies tack on more rules, regulations, and protocols; they tend to focus on short-term goals and lack the diversity needed to survive. As a result, they lessen their chances of achieving long-term survival. On the other hand, the longest surviving companies are those that are relatively modest in size, highly specialized, and operating in niche markets, like wineries, breweries, confectioners, and restaurants. So what do these scaling laws mean for the future of big business today? Simply put, it means that firms that seem invincible, like Google, Facebook, and Apple, will all eventually die off.

Scaling Raises the Question of Whether or Not Our Growing World is Sustainable

Now that you've learned how scaling affects organisms, cities, and businesses, it's time to discuss how these laws affect human life. Since the Industrial Revolution, the world's population has continued to grow rapidly; essentially, the Industrial Revolution has become like a Big Bang for population growth! In the year 1500, the world's population was only 500 million people. It wasn't until 300 years later in 1800 that the population doubled to 1 billion. 120 years later, the population doubled again and became 2 billion. It then took only 45 years to double again, reaching 4 billion in 1965. Our population will continue to grow super-exponentially, and we are on track to reach 12 billion by the beginning of the next century.

According to West, the Industrial Revolution has forced us to enter a new era, which he calls the Urbanocene, characterized by the exponential rise of cities. However, West also warns that as our population grows, our resources diminish. Our planet has only a finite number of resources available to us. Thomas Robert Malthus first identified this issue in his 1978 book *An Essay on the Principle of Population,* which predicted that the food supply would grow slower than the population, leading to the collapse of civilizations. In 1972, an organization called the Club of Rome expressed similar views in their study, *The Limits to Growth,* which demonstrated the catastrophic results of continuous population growth. This leads us to the question, *is our world sustainable?*

Put simply, no. As our population rapidly grows, we continue to strain the relationship between human society and nature. West argues that our planet would benefit from switching from a closed system - where energy is being used from our planet - to an open system, where energy is harnessed from the sun. You see, the total amount of energy delivered by the sun to the Earth is roughly 10^{18} kilowatt-hours a year, compared to our need of 1.5 x 10^{14} kilowatt-hours. In other words, our needs only make up 0.015

percent of the total energy supplied by the sun each year. Therefore, to create a sustainable environment, we would need technology that harnesses the energy from the sun, including its radiation, the wind, and tidal forces.

Unless the planet experiences paradigm-shifting innovation, the super-exponential growth the planet is experiencing will almost certainly result in a collapse of the system. We have experienced such innovations before with the discovery of bronze, coal, oil, technology, the internet, and more. However, the time passing between these cycles is only getting shorter and shorter. While thousands of years elapsed between the Stone, Bronze, and Iron Ages, less than 30 years elapsed between the recent Computer Age and the Information and Digital Age. This pattern suggests that we are due for another major paradigm shift in the next 20-30 years.

Ultimately, more innovations will be needed over shorter periods to “reset the clock” before the system can take off again. This means more innovation will be needed. But how many of these cycles can we go through? Is it sustainable to keep up with the ever-increasing pace of life? Or are we doomed? To address these issues, West believes we need to bring top thinkers together to create a grand unified theory to understand how the world works and to ensure our continued survival.

Final Summary

There are surprising similarities between diverse biological organisms, cities, and even companies. Scaling laws that govern the growth of each diverse being, city, and company reveal the illuminating inner workings of the world. Each organism, city, and company essentially follows three properties of the biological network. And like biological organisms, companies have an end date, a death. But will the world eventually meet the same demise? According to West, the growth of our world is happening too fast and if we don’t make some profound changes, then the world will experience catastrophic consequences. With the right innovations, however, we can ensure the survival of mankind.