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POWER IN NATURE

From Mitochondria to Emotion and Deception

> *The way in which mitochondria generate energy is one of the most bizarre mechanisms in biology. Its discovery has been compared with those of Darwin and Einstein. Mitochondria pump protons across a membrane to generate an electric charge with the power, over a few nanometers, of a bolt of lightning. This proton power is harnessed by the elementary particles of life—mushroom-shaped proteins in the membrane—to generate energy in the form of ATP. This radical mechanism is as fundamental to life as DNA itself, and gives an insight into the origin of life on Earth.*
>
> — Nick Lane, *Power, Sex, Suicide*

> *The maximum power principle can be stated: During self-organization, system designs develop and prevail that maximize power intake, energy transformation, and those uses that reinforce production and efficiency.*
>
> — Howard T. Odum, *Maximum Power*

> *Everything in the world is about sex except sex. Sex is about power.*
>
> — Oscar Wilde

POWER IS EVERYWHERE AND IS THE BASIS OF, WELL, EVERYthing. Without it, literally nothing can happen. Exploring the origins and evolution of power helps us better grasp how it shapes the human world today—and why our recently developed abilities to dramatically magnify and concentrate human power now threaten both humanity itself and the natural world on which we all depend.

While we have come to dominate other species and to transform our planet, and some of us have grown far wealthier and more influential than others, our powers are puny in universal terms. The universe is shaped by cosmic forces—gravity, which is nearly undetectable as an attractive force between two human-sized masses, but which shapes galaxies and the orbits of planets; nuclear fusion, which occurs due to forces in atomic nuclei and causes stars to emit enormous amounts of energy; and the electromagnetic force, which is responsible for the intense magnetic fields in rapidly rotating, charged black holes that can accelerate particles to spectacular speeds and energy levels. One particular star, our Sun, is the ultimate source of most power on our planet—whether it's the physical power of a hurricane, or the social power of a successful political movement (after all, the people who form that movement have to eat, and the energy in their food comes from the Sun).

The Sun radiates energy, largely in the form of light, far and wide throughout space, but only a tiny fraction of the Sun's total output falls on Earth. Even so, this minuscule portion is enough to heat the planet's surface so as to keep most ocean water in a liquid state, and to drive the weather that stirs our atmosphere.

Sunlight has also powered the most amazing development in the entire solar system—the evolution of living things. The process by which biological evolution got started is still the subject of research and speculation (we'll explore it more in a moment), but the results—after over four billion years—are all around us in the forms of millions of species of plants, animals, microbes, and fungi, and of complex ecosystems, each containing many species, each species adapted to others, and all adapted to particular regimes of moisture, temperature, and climate.

Every organism is able to capture some of the Sun's energy as that energy flows through Earth's systems.[1] And each organism has found a way to dissipate that captured energy in a controlled way. In doing so, every living thing wields powers of its own.

Indeed, evolution favors those organisms, and systems of organisms, that use power more effectively than others do. Early natural scientists and philosophers, including Gottfried Leibniz and Vito Volterra, deduced somewhat intuitively that evolution works this way, but the process wasn't described in detail or given a name until the 20th century. Ecologist Howard Odum, who worked on the problem in the 1960s by building on the earlier efforts of biophysicist Alfred Lotka, called this evolutionary tendency the *maximum power principle*. It's a key concept for understanding power anywhere and everywhere in the living world.[2] One way to think of this principle is that the species that exploits a given resource most effectively will tend to crowd out competing species.

But if evolution favors power maximization, then why didn't a single powerful organism emerge early in Earth's history and dominate the planet from then on? The diversity of life results from the fact that there are many ways to exert power, and many different environments in which to do so. As we'll see during the course of this book, one species *has* recently taken charge of virtually the entire planet as a result of its ability to maximize power in a host of ways—and we, of course, are members of that species.

However, many fundamental powers began to evolve in organisms long before humans appeared. While this book is mainly about the evolution of power in human societies, especially in recent decades, it's much easier to grasp the nature and sources of human power if we ground our exploration of the subject in the wider evolution of power throughout natural systems. Doing so also reminds us of some biological principles that we'll refer back to as we consider natural limits to the seemingly endless extension of human powers.

In this chapter, we'll take a look at some of the powers that arose in living things long before humans emerged. Then in subsequent chapters we'll see how humans have amplified these already existing potentials. We'll see how the drive for power makes us both cooperative and competitive; how all organisms have learned to limit their powers in order to develop and diversify; and how evolution turned higher animals like us into worshippers of beauty that are often willing to sacrifice some of our other powers for purely aesthetic purposes.

SIDEBAR 2

Powers in Math

Exponents, or *powers*, are a way of showing that a number is to be multiplied by itself repeatedly. In the expression 2^5, 2 is called the *base* and 5 is called the *exponent*, or *power*. 2^5 is shorthand for "multiply five twos together": $2^5 = 2 \times 2 \times 2 \times 2 \times 2 = 32$.

Powers of ten are often used to express really big and very small numbers. This is called *scientific notation*. For example, the total power of modern industrial civilization can be expressed as 4×10^{13} watts. In ordinary decimal numeric notation, that would be 40,000,000,000,000 watts.

When using scientific notation, increasing the exponent by one (i.e., multiplying the number by ten) is often described as increasing its *order of magnitude* by one. A quantity that is ten times greater than another is therefore said to be larger by an order of magnitude: 2.5×10^4 is an order of magnitude larger than 2.5×10^3.

To express very small numbers, negative exponents can be used: $10^{-3} = (1/10)^3 = 1 / (10 \times 10 \times 10) = 1/1000$. The number 10^{-4} is *an order of magnitude smaller* than 10^{-3}.

Scientific notation is useful in fields as varied as astrophysics, particle physics, biology, and engineering. It enables us not only to understand the vast variance in scale between the ultra-tiny and the incomprehensibly vast, but to operate across scales with technologies ranging from telescopes and microscopes to microprocessors, chemicals, spacecraft, and medicines. Powers of ten enable us to peer into the nucleus of an atom or estimate the size of the universe. They broaden our understanding while also greatly enhancing our ability to influence and control our environment.

The Basis of Life's Power

In the final analysis, life is all about power. Every living organism wields the powers of growth, metabolism, and reproduction. Whether a bacterium, a blade of grass, or a towering giraffe, all life forms capture energy from their surroundings and dissipate that energy in a controlled way to maintain steady conditions within the boundary that separates them from their environment. Even the simplest organism is a complex system able to control what's going on inside itself, and able to manipulate its environment in some way to get what it needs to sustain itself.

But how did life get started? Biologists have been puzzling over the question for at least the last couple of centuries. The process must have geared up remarkably early in Earth history. In 2017, researchers in Quebec found tiny filaments, knobs, and tubes—effectively, fossils of single-celled creatures—in rocks thought to be up to 4.28 billion years old. The planet itself is believed to have formed 4.6 billion years ago, so evolution apparently wasted comparatively little time in getting going.[3] These minute structures formed around hydrothermal vents at the bottom of ancient oceans; we'll see the significance of that in just a moment.

Until recently, some researchers thought the evolution of life must have begun with viruses, since they're much simpler than bacteria—they consist merely of bits of DNA or RNA wrapped in a protective coat of protein. But that theory has fallen out of favor. The problem is that viruses have no energy source: they depend on the energy of a host cell they've hijacked in order to reproduce themselves. Prior to the time such host cells existed, there would have been no way for viruses to have perpetuated themselves. Viruses must have evolved later. They likely started out as fully developed cells that gradually streamlined themselves by giving up their vital functions so they could more effectively piggyback on fully developed organisms.

The most intriguing and convincing current theory of the origin of living things centers precisely on energy and power. Billions of years ago, volcanic seepage sites spewed iron and sulfur into ancient oceans. Those ocean waters were acidic close to the surface, but alkaline further down close to the seafloor. Tiny iron-sulfur bubbles formed around the volcanic vents, with membranes often just a single molecule in thickness (similar bubbles can be observed today around deep-water volcanic vents). The outside of the bubble was more acidic than the inside. The membranes were also electrically conductive, and simple electrochemical processes would have shunted electrons to the inside of the bubbles, and protons to the outside. This inside-outside difference in acidity and charge could have generated a difference in electrical potential across the bubble membrane of several hundred millivolts—roughly the same level of charge that powers bacteria to this day. The process just outlined would supply not only a source of energy, but also the basis for the synthesis of biochemicals, including the proteins necessary for life—amino acids, peptides, and RNA.[4]

This story of life's origin is convincing because it describes a process—separating electrons and protons—that still generates energy in every living cell throughout all of nature. Everything that every cell does requires energy. And each of the three basic energy-generating processes of life—respiration, fermentation, and photosynthesis—involves proton pumping. The proton pump that started life's evolution over four billion years ago still powers all of life on Earth today.[5]

Just how powerful is life? Astoundingly, on a gram-for-gram basis, the average organism is 10,000 times as powerful as the Sun.[6] How could this be? The Sun generates an enormous amount of power, but it is also very massive. The math is simple: dividing luminosity by mass yields a mere 0.0002 milliwatts of power per gram for the Sun. A human, eating an average diet and converting that food energy into heat and work, averages two milliwatts per gram. Now, as we've seen, just about all the energy on Earth originated from the Sun, so life's power is derivative—it comes from somewhere else; in contrast, the Sun generates its own power. Nevertheless, the effectiveness of living things at appropriating and using energy is astonishing. Life is powerful indeed.

SIDEBAR 3

Measures of Physical Power

Leaving aside its social manifestations, power is, at its simplest, the rate of energy transfer. Think of energy as water flowing from a firehose. In terms of this metaphor, power is the rate at which water is emerging from the hose—which is determined by two factors: the diameter of the hose and the water pressure. If the hose is large but water pressure is low, there's not a powerful flow; likewise, if the pressure is great but the hose is small. If the hose is large and the pressure is high, you'll have a powerful flow on your hands. The total amount of energy (or, in the metaphor, water) that is released is determined by rate of flow (power) over time: a rate of flow of one liter per second would, naturally, yield sixty liters in a minute.

The unit of power most commonly used by scientists is the *watt*, named after the Scottish inventor James Watt (1736–1819). The watt is defined as the transfer of one joule of energy per second. How much is that? Using a hand crank, you can apply roughly eight watts of mechanical power. In terms of electrical power, a watt can run a single LED. *Energy* can be measured in watt-hours (power over time), as well as joules, calories, British Thermal Units (BTUs), therms, and other units.

Very small amounts of power can be expressed in terms of a nanowatt (one billionth, or 10^{-9} watt), a unit that can be useful in discussions about power in cell biology or the gravitational pull of a human-sized object. Large amounts of power can be measured in terms of a kilowatt (a thousand, or 10^3 watts), a megawatt (a million, or 10^6 watts), a gigawatt (a billion, or 10^9 watts), a terawatt (a trillion or 10^{12} watts), or a petawatt (one quadrillion, or 10^{15} watts). A typical modern middle-income American household can operate all its appliances using approximately one to three kilowatts of electrical power.

Sometimes power is discussed in terms of *horsepower* (hp). However, there are several different standards of horsepower. Two common ones are the *mechanical* (or *imperial*) horsepower, which is about 745.7 watts, and the *metric horsepower*, which is approximately 735.5 watts.

One horsepower is only vaguely equivalent to the power of an average horse—and therein lies a story. When he was developing the steam engine, James Watt was visited by a brewer, who requested an engine that could match the power output of his biggest and strongest horse. Watt accepted the challenge and built a machine that exceeded the power of the brewer's horse; it was the output of that machine that became the basis for horsepower.

So, how much power can an actual horse apply? A 1993 paper in *Nature* by R. D. Stevenson and R. J. Wassersug cited measurements made at the 1926 Iowa State Fair, where one horse was recorded at peak power over a few seconds at 14.9 hp (11.1 kW). However, they observed that for sustained activity, a work rate of about 1 hp (0.75 kW) per horse is indeed realistic.

A healthy human can produce about 1.2 hp (0.89 kW) briefly and sustain about 0.1 hp (0.075 kW) for longer periods; trained athletes can manage up to about 2.5 hp (1.9 kW) briefly and 0.35 hp (0.26 kW) over several hours.

Three Big, Powerful Families

The earliest cells must have been simpler than today's single-celled organisms, which are the beneficiaries of billions of years of evolution: even though they're tiny, they are highly organized internally and have diverse and sophisticated ways of making their way in the world. Today there are three broad kinds of cells, and therefore three branches of the tree of life: bacteria, archaea, and eukaryotes. Bacteria are almost certainly the oldest of the three.

Bacteria and archaea exist only as single-celled organisms (unless you count a bacterial colony as an organism: in some colonies of Myxobacteria, individual bacteria specialize). They are also similar in that they lack nuclei. For a long time, biologists assumed that archaea *were* bacteria, but as more about them was discovered, it became clear that these are two fundamentally different kinds of life forms.

Most bacteria are shaped like rods, spheres, or spirals. Most are also tiny, 0.5 to 5 micrometers in length, though a very few, such as *Thiomargarita namibiensis*, are up to half a millimeter long—big enough to see with the naked eye.

An individual bacterium is like a battery. The cell continually pumps protons out across its membrane into the periplasmic space between the membrane and the outer cell wall, thereby creating an electrical gradient. It does this by gathering electrons from its environment, passing them along a chemical chain, and using their combined negative charge to pump the protons outward. The creation of an electrical gradient around the bacterium can be compared to blowing air into a balloon: pressurized air can later be used to do work, like turning a pinwheel; the electrical potential around the bacteria can be used as well, for work such as chemical synthesis and reproduction. Bacteria can even use their proton-pumping force to power locomotion.

In order to maintain their electrical gradient, bacteria must have a source of extra electrons, and they have evolved several strategies for getting them. Some bacteria derive their electron energy from light

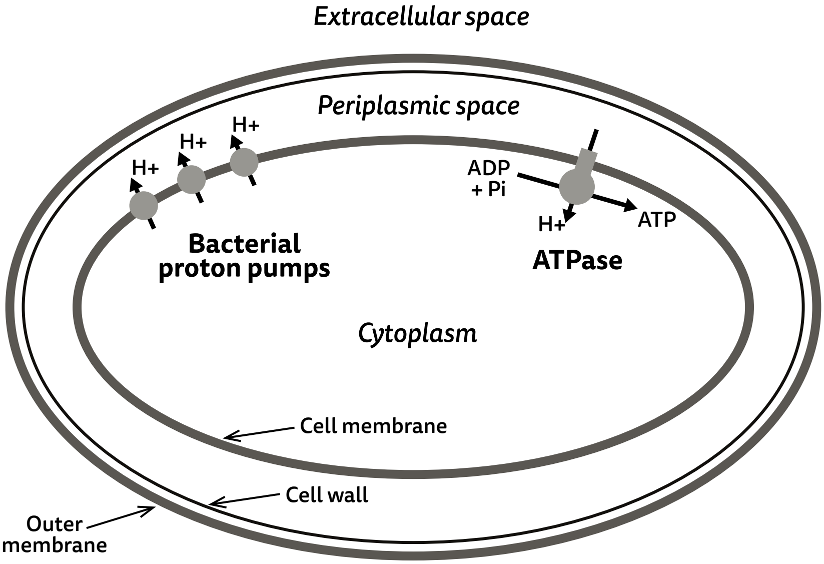

Figure 1.1. Proton pumping in a bacterium (highly simplified).

Source: Adapted from an illustration by Steve Mack, MadSci Network.

through photosynthesis. Others, called chemotrophs, use chemical compounds as a source of electrons (see "Power of Eating," below). Chemotrophs are further divided by the types of compounds they use. Ones that use inorganic compounds like hydrogen, carbon monoxide, or ammonia are called *lithotrophs*, while those that use organic compounds are called *organotrophs*. Within bacteria, a different compound must receive the electrons from "food" in a chemical reaction in order for the cell to obtain and use energy; aerobic bacteria use oxygen as the electron acceptor, while anaerobic bacteria use compounds such as nitrate, sulfate, or carbon dioxide.

Even though bacteria generally lack the ability to form complex, multicelled individuals, they have evolved the ability to live in extremely varied environments (hot or cold; with air or without air; acidic or alkaline). They are also so good at producing such a huge range of chemicals that industrial biochemists are constantly finding new ways of harnessing them for commercial applications.[7]

Although archaea were at first thought of as bacteria, their genes are significantly different from those of bacteria, as are their cell walls and other cell structures, and so is their energy metabolism. They were "discovered" only in 1977, and are extremely difficult to culture and study in the laboratory. Only 250 species have been identified (compared to some 30,000 kinds of bacteria).[8] Genetic differences suggest that archaea and bacteria probably split from a common ancestor 3.7 billion years ago. Though they are less numerous in the gut than bacteria, archaea are still plentiful in your digestive tract and on your skin.[9]

Eukaryotes, which have cell nuclei, appeared more recently, about 2.7 billion years ago. Unlike bacteria and archaea, they were able to form complex multicelled individuals: all plants, animals, and fungi are eukaryotes (you're a eukaryote and so am I, glad to meet you!). Even single-celled eukaryotes can be vastly larger and more complicated than typical bacteria or archaea. They're able to grow so big because they found a way to delegate their energy production activities to mitochondria—vital internal cellular structures we'll explore in more detail in a moment.

ATP Power

We have seen how bacterial cells generate an electrical potential by pumping protons into the space between their cell membrane and their outer cell wall. But how do they actually use that power? In any energy-using system—such as an organism, a household, or a city—it helps to have a medium for storing and transferring energy. In a typical medieval household, firewood served that function; in modern cities, gasoline is one of our primary media for storing and transferring energy. Adenosine triphosphate, or ATP, is the firewood or gasoline of the cell.

The primary energy-yielding activity of the eukaryote cell is respiration, which, at the cellular level, is the breaking down of glucose (food) with oxygen. (There's also an anaerobic pathway for ATP creation—fermentation, which yeast are really good at…Care for a beer?—but let's stick with respiration, because it's more relevant for understanding the energy pathways in most plants and animals.) As a result of various chemical transformations, one molecule of glucose will yield up to 36 molecules of ATP, which can be stored or circulated until needed. The ATP molecule features a chain of three phosphate atoms; when the third of those atoms is broken off through a chemical process, ATP becomes ADP (adenosine diphosphate) and energy is released and available for immediate use. The ADP can then be recycled by adding back another phosphate atom (which, of course, requires energy). ATP is actually better than firewood or gasoline, in that it can be endlessly recycled!

In bacteria, energy generation can take many routes, but all have one process in common: the electrical potential that develops across the inner membrane, which generates a proton-motive force that drives protons through a molecular structure known as the ATP synthase complex, generating ATP from ADP by adding a phosphate atom to the chain. (By the way, if this sounds complicated, it is—there are many textbooks devoted to explaining it, and researchers are still learning more about the energy pathways of super-tiny individual cells.)

Cells use the energy from ATP for just about everything they do, including synthesizing DNA and RNA. Bacteria and archaea make ATP in ATP synthase complexes on the cell membrane; in eukaryotes, those structures are located in mitochondria. Now's the time to talk about these remarkable structures.

Mitochondrial Power

Eukaryotes differ from bacteria and archaea not just because the former have nuclei, but also because they have organelles, which are like cells within the cell. The most important of the organelles are mitochondria, of which there may be hundreds in each eukaryote cell.[10]

Mitochondria generate virtually all of a eukaryote cell's ATP. They look like bacteria, and that's because they once were free-living bacteria that took up residence inside larger cells (probably a type of archaea) some two billion years ago. They have their own genomes, separate from the cell's genome that's housed in the cell nucleus.

Eukaryotes have a cell membrane but, unlike bacteria, no rigid cell wall. That means they cannot use the space between membrane and wall as a battery, the way bacteria do. The ancestors of eukaryotes had cell walls, but once they acquired mitochondria it was possible to tear down that wall and delegate energy generation to their mitochondria.[11] Ditching the cell wall meant that eukaryotes could change shape and become true predators—like the amoeba, which engulfs its prey (see "Power from Eating," below).

Within mitochondria, proton pumping occurs across a highly folded inner membrane. The cell delivers electron source material to the mitochondria; the latter then store the energy from the source material as ATP, and deliver the ATP to the cell for all its various energy-using functions. This neat trade-off made complexity possible.

The Power of Complexity

For bacteria, not having mitochondria is a limit on size. Double the size of a bacterial cell and it can produce only half the ATP per unit of volume; meanwhile the larger cell needs *more* energy for all its cellular functions. That's why bacteria, on the whole, have stayed extremely small.

Not so the eukaryotes. Single-celled eukaryotes can be hundreds, even thousands of times the size of a typical bacterium. Need more energy? Just make more mitochondria! Once energy production was delegated to mitochondria, cells could grow larger, and also join each other in coordinated groups in which they each took on specialized tasks.

Mitochondria made complexity possible; natural selection made complexity attractive. Bigger, more specialized, and more complex creatures could more efficiently exploit resources or escape predators. Natural selection acted like a ratchet, turning random variation into a trajectory. And that trajectory has led us up the ramp of complexity.[12]

If eukaryotes with mitochondria hadn't evolved, the story of life on Earth would have been all about single-celled bacteria and archaea.

Animals and plants would never have seen the light of day if it hadn't been for that incident, two billion years ago, when a primitive bacterium took up residence inside an archaeon and they found a mutually beneficial way to live and work together. This may have been a fluke, unlikely to be duplicated in bacterial colonies on other planets throughout the universe. If that's the case, complex life may be unique to Earth.

Gene Power

Consider the lowly *Escherichia coli*, usually known by its nickname *E. coli*, one of the many species of bacteria found in the human gut. (You are probably host to millions of them right now.) An organism that can live with or without air, *E. coli* is harmless in most of its strains—but some forms, if ingested, will make you very sick. These tiny rod-shaped critters derive their energy from semi-digested food in the lower intestines of animals, from feces, or from prepared cultures in Petri dishes (*E. coli* are by far the most popular subjects for lab experiments, so scientists know a lot about them).

Though it is one of the simplest organisms and its size is measured in microns, each individual *E. coli* has a cell wall composed of cellulose, plus a plasma membrane and all the various proton-pumping and ATP-generating equipment discussed above. Internal systems regulate its functions and transport materials through its cell wall to spots where metabolism occurs. Altogether, the *E. coli* cell is like a tiny factory, with control centers, energy production sites, and chemical synthesis chambers. It also contains a string of DNA organized as genes. Without this DNA string, the *E. coli* cell would not be able to organize and reproduce its other structures.

All living organisms are made up of cells (in many cases, like *E. coli,* only a single cell) that contain genetic material. In bacteria and archaea, DNA is just a single strand floating in the cell's cytoplasm. In eukaryotes, DNA is stored in the cell's nucleus. Wherever you find it, DNA acts as a blueprint for the manufacture of proteins, which the cell uses for everything it does.

Genes conserve the organism's basic structure and functions through generations of reproduction. As the building blocks of heredity, genes also confer the power of mutation, enabling successive generations to adapt to environmental change. Mutations, however, can pose a risk: many actually reduce the cell's viability and the organism's survival potential; that's one of the reasons why nuclear radiation, which triggers higher rates of random genetic mutations, is generally to be avoided.

The Power of Reproduction

While single-celled organisms like *E. coli* reproduce through cell division (mitosis), most multicelled plants and animals have adopted sexual reproduction. Either way, the power of reproduction is one of the keys to life's success. Reproduction enables any given type of organism to grow in number, taking advantage of more resources and occupying more territory—hence maximizing its collective power.

The reproduction of any cell requires energy, some of which is used for copying the DNA blueprint. Mistakes in copying can be expensive or even deadly.

The vast potential of reproduction is illustrated in the concept of "doubling time"—the amount of time in which a species can double its population size. Imagine a pond with a patch of algae on its surface. If the algal population grows at ten percent per hour, the total number of algae will double every seven hours. If the algae occupied one-twentieth of the pond surface when our observations started, they would take up one-tenth of the surface after 7 hours, one-fifth after 14 hours, two-fifths after 21 hours, and four-fifths—nearly the entire surface—after a mere 28 hours. The compounded, or exponential, growth of any physical system accelerates until it hits a limit—such as the boundaries of the pond's surface, in our example.

Bacteria can reproduce much faster than that. They can divide every 20 minutes, through an energy-intensive process that requires making a complete copy of the entire DNA blueprint. Starting with a single bacterium, if doubling continued for just two days, the resulting colony would weigh 2,664 times the weight of the Earth.[13] Obviously, this never actually happens. That's because bacteria are normally half-starved, and when they run out of food they pass into a nearly inert state in which their rate of mitosis slows dramatically.

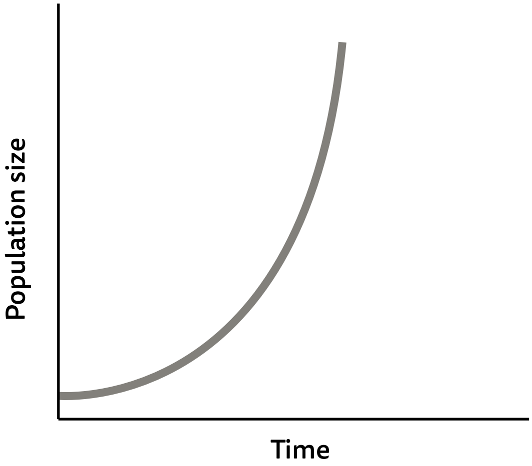

Figure 1.2. Exponential growth.

It's worth noting that even though humans reproduce far more slowly than bacteria or algae, the doubling-time principle still holds. At one percent annual population growth rate (which is lower than the current global average), the total human population doubles in about 70 years. In reality, one billion humans—our global population level in 1820—became two billion in 1927, four billion in 1974, and we are roughly eight billion today. While population growth confers the advantage of greater collective power, it runs the risk of overwhelming limited resources. Hence some human societies (such as China and Cuba in recent decades) have sought to moderate population growth, partly as a way of staving off resource scarcity, while other societies (including ancient states in Mesopotamia and China, and European-Americans during the 18th and 19th centuries) have deliberately sought to increase their population growth rate as a way of competing with other societies or maximizing their power in other ways.

The Power of Self-Limitation

Complexity confers benefits, as discussed above. But it also entails costs and trade-offs.

To live in a multicelled organism, each cell must submit to the severest of limits—death. If cells didn't die, the multicelled organism couldn't live. That's because individual cells eventually wear out or become damaged; if the body had no way of eliminating and reabsorbing them, whole subsystems would become dysfunctional fairly quickly, imperiling the entire individual. This does happen occasionally anyway, and the result is cancer. To prevent this, cells are programmed to commit suicide when instructed to do so by a molecular "police force." It turns out that mitochondria and power play key roles: the loss of electrical potential across the folded membranes within the mitochondria of a cell is a trigger that invariably leads to cell suicide.

This self-subordination of the individual to the needs of the whole is seen also in groups of highly cooperative organisms, such as ants. Among exploding ants (*Colobopsis saundersi*, found in Malaysia and Brunei), workers produce a toxic fluid in their abdomens; when the colony is attacked, some of the workers sacrifice themselves by exploding, releasing the toxin and killing the invaders. Self-limitation and self-sacrifice might seem to contradict the maximum power principle. They don't, because groups of ultra-social creatures act as superorganisms; in these cases, evolution is acting at the group level, rather than the individual level. We'll explore that concept further, especially as it relates to humans, in chapters 3, 6, and 7.

Power from Photosynthesis

Photosynthesis, which powers nearly all multicelled life on Earth, got its start in cyanobacteria, which appeared around 2.7 billion years ago. The chemistry of photosynthesis essentially runs respiration backward. Respiration uses glucose and oxygen to make water, CO_2, and energy; photosynthesis uses energy (from sunlight) plus water and CO_2 to make glucose and oxygen. Plants use some of the glucose they make to fuel respiration and release energy; the rest is incorporated into their tissues and becomes leaves, stems, and roots.

Within plant cells, photosynthesis takes place in organelles called chloroplasts. These appear to have originated as cyanobacteria (i.e., bacteria able to perform photosynthesis), which, roughly 500 million years ago, found a cozy living arrangement within some eukaryote cells, much the way mitochondria had already done.

Green plants have the ability to use the energy of sunlight directly to build body tissues from little more than air and water. (Plants also need nitrogen, phosphorus, potassium, and trace elements, but these do not make up the bulk of plant tissues.) In doing so, they store energy in the chemical bonds between the atoms of carbon, hydrogen, and oxygen that make up the carbohydrates composing a plant's body. The power of photosynthesis has enabled green plants to spread across the surface of the planet, wherever there are sufficient water sources and nutrients; plants (most often in the forms of phytoplankton and kelp) are also dispersed throughout suitable areas of oceans, streams, and lakes.

It is largely through photosynthesis that the Sun's energy is able to power multicelled organisms throughout the biosphere. Biologists call green plants "producers," because they essentially make their own food—as opposed to "consumers" (a category that includes all animals), which have to eat other organisms or products of organisms to obtain their energy.

Power from Eating

By eating other organisms, consumers obtain the energy that is the source of their powers. At the same time, eating requires the exertion of energy; on a net basis, the energy derived from food must exceed the energy required to obtain and eat food if the organism is to survive.

Bacteria are able to transport food through their cell wall by secreting enzymes onto the food to break it down into simpler forms that can be transported through the wall. Eukaryote cells, which don't have rigid walls, are able to transport nutrients directly through the thinner cell membrane. The first true predators were eukaryotic cells that were able to engulf their prey (mostly bacteria, algae, and particles of formerly living cells) by flowing around it and enclosing it as a food vacuole, within which it could be digested. This process, known as *phagocytosis*, is how the amoeba and many other protozoa still make their living.

Eating is easier to understand intuitively in big, multicelled animals, because it's an activity we ourselves engage in frequently—sometimes with great pleasure. Herbivores eat plants. Carnivores eat other animals; secondary carnivores, like many snakes and fish, eat other carnivores. Decomposers, such as fungi, eat the dead bodies of other organisms, gradually turning them into soil—which helps support the growth of producers.

When a whitetail deer (an herbivore) stops along its journey through a meadow to eat a dandelion (a producer), only about a tenth of the dandelion's total energy stored as carbohydrate can be absorbed and used to power the animal. Similarly, when a mountain lion (a carnivore) stalks and kills that deer, only about a tenth of the total energy is transferred. Biologists often describe the overall results in terms of a food (or energy) pyramid by which energy moves through the ecosystem. At each stage, most energy and materials are lost as heat and waste rather than being converted into work or bodily tissues. Thus, a typical terrestrial ecosystem can support only one carnivore to ten or more herbivores of similar body mass, one secondary carnivore to every ten or more primary carnivores, and so on.[14]

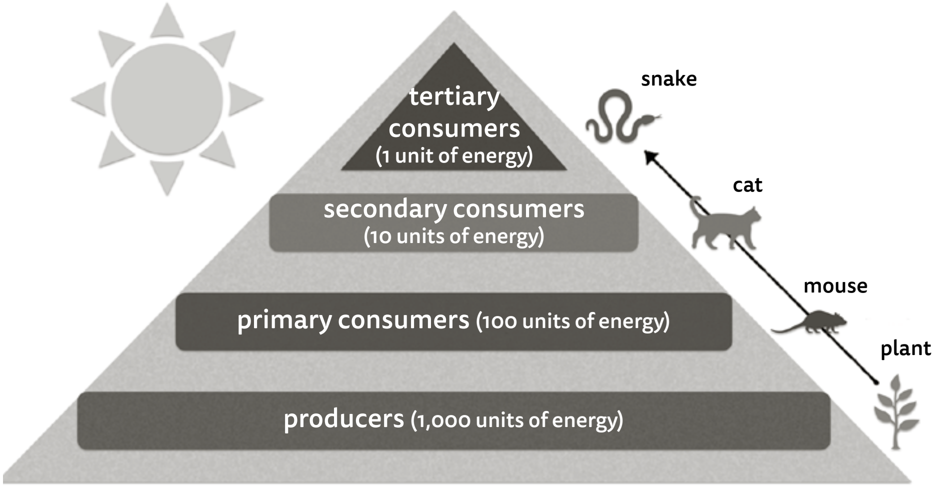

Figure 1.3. The energy pyramid in nature. Credit: Post Carbon Institute.

Think of the energy pyramid as a visualization of power getting distributed through the biological world: it enters at the bottom and works its way up, at each level becoming more "concentrated" (Howard Odum termed this "concentration" of energy *transformity*). Yet organisms at the base of the pyramid, as a result of being far more numerous and having far greater total biomass, are collectively just as powerful, in their way, as the top predators at the pyramid's apex (though humanity's use of fossil fuels has temporarily upset that balance, as we'll see later on).

Power and Bodies

The Power of Size

We've already discussed some of the advantages of bigness, but there's a lot more to say on this score. On average, larger animals have a slower rate of metabolism and enjoy a longer life than smaller ones. The important thing to note is that their individual cells actually need fewer nutrients: as biologist Nick Lane colorfully puts it, "an elephant-sized pile of mice would consume 20 times more food and oxygen every minute than the elephant itself does."[15] A mouse has to eat half its body weight every day to fend off starvation, while a human survives eating only two percent of body weight daily. It turns out that, as animals get bigger, their metabolic rate slows by a factor that roughly corresponds to the ratio of surface area to mass. This is known as Kleiber's law, one of the power laws of biology.

There are two ways of looking at this situation. First, the cheery way: being big offers the advantage of efficiency and economy of scale. The less cheery way: this increase of efficiency with growth in size is at least partly a result of the burgeoning bulk of the supply network required to deliver food and oxygen to each cell; as the network grows, it forces constraints upon the animal's individual cells and their mitochondria, so these cells have to economize on energy and they're not able to work as hard. Therefore, the ratio of the animal's maximum power to its weight falls with size.

When it comes to lifespan, size seems to confer a less ambiguous advantage. The mouse lives two years on average, while the elephant

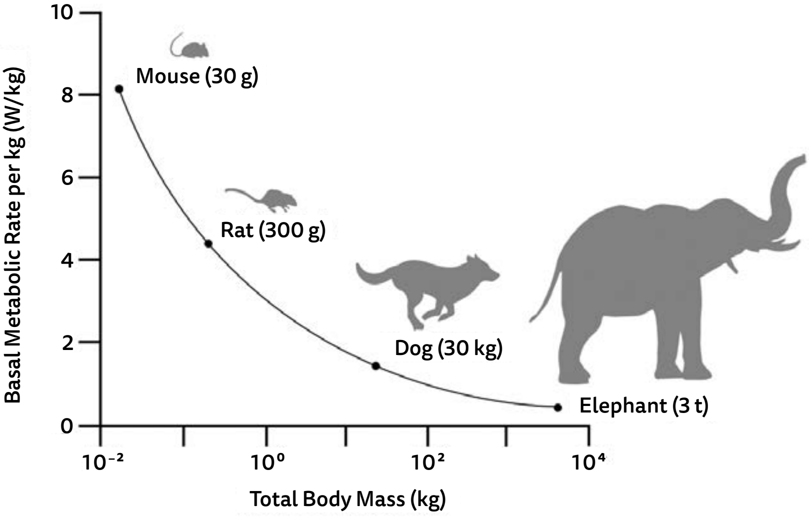

Figure 1.4. Visualization of Kleiber's law.

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may live a hundred years. Altogether, the mouse is working harder and burning out quicker. However, there are a few anomalies in the size-lifespan continuum. Birds, bats, and humans live longer than they should, based on their size: a pigeon may live 35 years, while a similar-sized rat lives only two. Many humans live longer than they otherwise would due to modern medicine, but it appears that the long lives of birds and bats are due to a genetic adaptation having to do with the production and accumulation of free radicals within cells. Scientists are trying to better understand what helps birds live so long (some seabirds appear entirely immune to the diseases of old age) and to see whether humans could benefit from that knowledge.

Some additional advantages of bigness: being of larger size aids in retaining heat; offers greater strength; reduces problems having to do with water surface tension (insects have a hard time taking a drink); and tends to optimize the functioning of organs such as eyes, which are composed of cells of fixed size (more cells, better vision—or that's the theory, anyway; I had to wear glasses when I was a kid despite having eyes bigger than a hawk's).

But there are also some additional disadvantages to bigness that are worth mentioning: larger birds have to work harder to fly, and larger mammals struggle to make their way through thick vegetation or to walk on boggy ground. For a tiny animal, falling down is no big deal; for an elderly human, it can be fatal.

Muscle Power

There are lots of kinds of specialized cells within larger multicelled organisms. Let's look at just two kinds, muscles and neurons, which often work together and are particularly important for developing many of the unique powers enjoyed by animals such as ourselves.

First, muscles. They are the source of animals' powers of lifting and moving (see "Powers of Motion," below). But muscles do more than this: they are essential for breathing and for moving blood through veins and arteries (the heart is a muscle) and food through the digestive system.

Muscles are made of long, thin cells grouped into bundles, or fibers. They're powered by ATP (of course), and controlled by neurons. When a muscle fiber gets a signal from its nerve, proteins and chemicals release energy to either contract the muscle or relax it.

Muscles make up about 40 percent of the total weight of a typical human, and perform many specialized tasks including moving the eyes and protecting the inner ear from loud noises.

Neuron Power

If muscles supply the brawn for animals, neurons are literally the brains—as well as providing the signaling channels for brains to convey their messages. Outside the brain, there are three types of neurons: sensory, motor, and interneurons (which connect spinal motor and sensory neurons). But within the brain, there are so many kinds of neurons that they are hard to neatly classify.

Neurons get their messages across to other neurons using neurotransmitters. These are chemicals that can excite, inhibit, or modulate a neuron's activities. There are dozens of neurotransmitters, including dopamine. The brain has many dopamine pathways, and this particular neurotransmitter is involved in motor control, behavioral reward and reinforcement, and motivation. We'll discuss dopamine more in Chapter 6.

Most neurons have a cell body, an axon, and dendrites. The axon extends from the cell body and often branches several times before ending at nerve terminals. Dendrites receive messages from other neurons, and are covered with synapses connecting them to axons from other neurons. The nervous system is a communications marvel.

The human brain contains, on average, 100 billion neurons, and operates at about 23 watts of power during wakefulness. Compared with electronic computers, this is an amazing level of power efficiency. While it is impossible to calculate precisely, the human brain's computational power has been estimated at a billion billion calculations per second. The world's fastest supercomputer, using several megawatts of power, takes over half an hour to do what the human brain does each second.[16]

The Power of Sex

Asexual reproduction by way of mitosis has worked fine for bacteria and other single-celled creatures for billions of years. Why wasn't it maintained in all bigger, multicelled creatures via self-cloning?[17] After all, the alternative—sexual reproduction—reduces reproductive opportunities: with two sexes, reproduction is only possible with, at best, half the members of your species. Finding a mate can take time and effort, and there's no guarantee of success. Therefore, there must be some advantage that outweighs that cost.

The advantage is genetic diversity. Among animals, males contribute sperm while females contribute eggs. Both pass along genes to the offspring—but only the mother passes along mitochondria (and their genes) to the next generation.[18]

Sexual reproduction generates unique and often beneficial combinations of genes that in most cases have already proven not to endanger survival. Greater genetic variety helps, for example, by increasing the chance that some of a population of bees, soybeans, or blackbirds will survive if a deadly infection occurs.

Of course, sex introduces the possibility for all kinds of social power intrigues, imbalances, and abuses, some of which we'll explore further in later chapters. But in addition, sexual reproduction opens the door to sexual selection and beauty, which we'll turn to in a moment.

Powers of Perception

Sense organs give organisms powers to adapt to their environments, find food, locate potential mates, and avoid predators. Seeing, hearing, feeling, tasting, and smelling are only the most familiar of the possible senses, which also include the abilities to detect the Earth's magnetic field and to judge spatial orientation and degrees of moisture and acidity.

Among animals, champions of perception include dogs, whose noses are about 40 times more acute than our own; birds, which have an ultraviolet color receptor in their eyes and can therefore see a whole "dimension" of color that's invisible to us; and bats, whose hearing can distinguish high-pitched echoes accurately enough and quickly enough to enable them to locate and catch flying insects.

Plants don't have neuronal networks the way higher animals do. Nevertheless, plants have perception. Nearly all exhibit photosensitivity and the ability to sense orientation in space (i.e., they perceive and actively respond to gravity). Most are also sensitive to an array of chemicals in the soil or air, which are sometimes interpreted either as warnings of inhospitable conditions or as invitations to bloom and reproduce. Some plants are even able to detect the amount of soil around them and adapt their growth accordingly, regardless of the availability of nutrients.

Powers of Motion

Because animals eat other organisms, they often have to travel to find their next meal.[19] They may also have to travel in order to find a mate. Animals ooze, creep, jet, swim, slither, crawl, walk, run, jump, fly, and reach. If you've ever watched swallows catching flying insects, you probably share my admiration for these avian aerial acrobats. Even the lowly single-celled amoeba (which isn't really either an animal or a plant) has the power to extend and retract pseudopods—arm-like projections of cytoplasm—in order to move and to reach for food.

Most plants, able to take advantage of ambient sunlight, stay in one place; however, plants do have limited ability to move, as can be observed by watching a sunflower bend its head toward the changing relative position of the Sun throughout the day. Plants also use air currents, or other organisms, to move their seeds and pollen far and wide. And communities of plants, such as forests, can slowly shift their range in response to changing climate conditions—as many North American trees did at the end of the last Ice Age, moving their range by up to 30 miles per century (a speed that may not be fast enough to enable many tree species to adapt to current human-driven climate change). Some plants move parts of themselves quite rapidly: the Venus flytrap closes its trap in about a hundred milliseconds, while the white mulberry tree can catapult pollen from its flower stamens at a velocity of over half the speed of sound.

The Power of Warm Blood

Warm-blooded animals (biologists call them *endotherms*), such as mammals and the lineage of dinosaurs now restricted to birds, have a power advantage over cold-blooded animals (*ectotherms*), which include reptiles, amphibians, and many aquatic vertebrate and invertebrate lineages. When animals gained the ability to closely regulate their own temperature, they could stay active in spite of daily and seasonal temperature variations that send ectotherms into hiding or inactivity. This gave endotherms a higher baseline demand for energy but also the ability to forage for energy much more of the time. Therefore, in many environments, the average power output of an endotherm is much higher than the average power output of an ectotherm; this enables endotherms to outcompete ectotherms for resources. An evolutionary example of the maximum power principle at work!

But this advantage comes at a cost. If a reptile and a mammal maintain the same temperature, the mammal needs to burn six to ten times as much fuel. If the outside temperature falls, the difference grows: in cold weather, the reptile uses less energy than in warm weather, while the mammal uses more. On average, a mammal uses 30 times as much energy as a same-sized reptile. This translates to more meals eaten more often—and more work in obtaining food. That's why birds and mammals tend to have much more stamina than reptiles (i.e., they can maintain a higher pace of work for longer). For this reason, mammalian and bird muscle cells tend to have far more mitochondria than muscle cells in snakes.

Thus, it turns out that there are advantages to both endothermy and ectothermy—which is why there are still reptiles, even though there are also birds and mammals.

Power and Behaviors

Powers of Emotion

We know that emotions can be powerful. They can cause us to flee danger, fight an attacker, or risk humiliation and rejection in pursuit of a mate. Emotions are also key to social life: through them, we communicate urgent motives and maintain group cohesion. As such, emotions have played an essential (though still largely unexplored) role in evolution.

New research is showing that emotions are everywhere in nature. Primatologist Frans de Waal, who has spent decades studying the behavior of chimps and bonobos, has concluded that there may be no uniquely human emotions. Similarly, observing my backyard flock of chickens on a daily basis, I see clear expressions of rage, joy, contentment, jealousy, fear, curiosity, and affection; they can hold grudges or choose to forgive past insults. These birds, which are highly social, are also very emotional creatures.

Do plants have emotions? A couple of decades ago, only a tiny minority of scientists would have said that they do, but that is changing. Plants respond to opportunity and threat—even threats to their neighbors. In one experiment, deliberate damage to a cucumber plant caused measurable chemical responses (fear?) in nearby chili peppers and lima beans.[20]

But plants don't have brains or neurons; how, then, could they possibly feel emotion? The answer may have to do with *convergent evolution*, in which organisms not closely related evolve similar traits through different pathways in order to solve similar problems. Moths and geese fly, but they have found anatomically different ways of doing so. In the same way, both animals and plants appear to exhibit what might be considered emotional responses, transmitted on one hand by neurons, on the other by volatile chemicals and what researcher Kat McGowan has called "electrical pulses and voltage-based signaling that is easily reminiscent of the animal nervous system."[21]

Powers of Intelligence

The abilities to discern cause and effect, and to remember, imagine, compare, and plan ahead offer higher animals with lots of neurons the advantage of being able to foresee the behavior of prey, predators, or competing members of the same species, and to devise strategic responses.

For decades, most scientists assumed that only humans exhibit intelligence. In recent years, however, that attitude has shifted dramatically. Research has shown that all living things have at least some vestiges of cognition.[22]

Most scientists have tended to assume that the animals most like ourselves (i.e., other primates) must be the most intelligent. Yet elephants, porpoises, and many birds (such as corvids, parrots, and starlings) are champs at remembering, counting, calculating costs and benefits, and doing lots of other things we associate with being smart.

Further, intelligence is certainly not limited to vertebrates. In her book *The Soul of an Octopus*, Sy Montgomery shares her alternately eerie and heartwarming experiences with cephalopods—"alien" intelligences who easily recognize and remember particular people, display unique personalities, and, if kept in captivity, can devise ingenious and detailed plans of escape.

As with emotion, it was long the assumption of scientists that, without brains, plants are incapable of the basic functions of cognition. Yet new research shows that plants nevertheless exhibit clear signs of intelligence—of which the ability to plan is generally agreed to be a key. Anthony Trewavas, writing in *Trends in Plant Science*, notes that

> Branch and leaf polarity [i.e., relative growth patterns] in canopy gaps have been observed eventually to align with the primary orientation of diffuse light, thus optimizing future resource capture. The internal decisions that resulted in the growth of some branches rather than others were found to be based on the speculatively expected return of future food resources rather than an assessment of present environmental conditions.[23]

Once again, convergent evolution seems to have provided plants and animals with different pathways to the same power.

Powers of Deception

The ability to deceive predators, prey, potential mates, or rivals of the same species can sometimes confer a power advantage. Both animals and plants have learned to deceive by mimicking other objects or organisms.

The *Kallima* butterfly in Sumatra has wings that closely match the color and shape of dead leaves, thus tricking potential predators to ignore it. Other edible butterflies mimic the color and behavior of toxic insects in order to avoid being eaten. The power of deception can also be deployed on an offensive basis: the bolas spider hunts by releasing an odor that exactly matches the one given off by female moths ready for mating.

Plants are just as good at deception as animals. Stinging nettle, as the name implies, delivers a nasty surprise to those who touch it. A plant of the mint family, known as dead nettle, likes to grow nearby; it looks just like stinging nettle and, though it isn't painful to the touch, is avoided by browsers and thereby benefits from the association. Other plants (such as the bee orchid and tongue orchid) use color, shape, and smell as sexual lures to attract pollinators, which believe they are approaching a potential mate.

Deception can even be used to get others to do the work of parenting for you. The cuckoo is a notorious trickster, laying its eggs in the nests of other bird species, which rear the cuckoo chicks as their own. Cuckoos are even able to change the color, shape, and size of their eggs to match the appearance of the host species' own eggs.

Powers of Communication

Communication is the basis of social power—which existed long before humans. Cooperation requires communication, and extreme cooperation (as among ants) requires an almost constant exchange of information. Communication is also essential for deception, mating, hunting, and avoidance of predators. It can occur through sounds, visual displays, scents (i.e., chemicals), heat, electromagnetic fields, or vibration; and it can be intentional or unintentional. When it results in a behavior change in the receiver, researchers call it a signal.

Ants use body language, scent, touch, and sound to navigate their hypersocial world. Each colony has its own cocktail of pheromones, so any two ants can instantly smell whether they are relatives and teammates, or from rival colonies. If an explorer ant finds some interesting food on her travels, she will lay down a scent trail as she hightails it back to her colony to inform the other workers. She even describes (by antenna touching and body language) what to expect at the end of the trail. If a part of the underground colony collapses, the trapped ants will scrape their legs on a washboard-like section of their bodies to make a sound that alerts the rest of the colony.

Birds are also enthusiastic communicators, but only recently have researchers begun to appreciate the range of possible avian signals. Nearly everyone is familiar with the sound of crows, but that insistent "Caw! Caw!" conveys far more useful information to other crows than it does to nearby humans. Not only does each crow recognize the sound of other individual crows, but these birds are able to share remarkably detailed and specific information about their surroundings. In crow-speak, the same call can mean different things depending on tone, timing, the space between repetitions, and speed of utterance.

In the wild, parrots use body postures, their eyes, and their feathers to communicate, along with a wide variety of vocalizations—which vary from region to region, like human dialects. In captivity, parrots are easily able to mimic the sound of human speech. More impressively, where researchers have taken the time to teach them the names of objects and actions, parrots have learned to form meaningful sentences, commenting on what they see and how they feel, and asking for what they want.

Similarly, chimps and gorillas have been taught to use sign language. Washoe, the first chimpanzee to learn American Sign Language, could communicate with approximately 350 signs; Koko, a gorilla born at the San Francisco Zoo, understood about 2,000 words of spoken English, in addition to 1,000 signs.

Researchers are still only beginning to understand the communication abilities of cetaceans—dolphins and whales. These sea mammals rely primarily on sound for communication (a dolphin's hearing range is six times broader than a human's), as well as for echolocation. Each pod of dolphins has its own dialect, and each dolphin uses a unique signature whistle—imparted by its mother—by which it is known. Groups communicate in order to hunt more effectively, and the pod is able to stay together because individuals keep within hearing range of one another.

Plants communicate using electromagnetic and chemical signals that seem to mimic the functions of neural circuitry in animals. For example, wounded tomato plants give off the volatile odor methyl jasmonate, which researchers believe acts as an alarm signal for neighboring plants. The neighbors can then prepare for attack by producing chemicals that either defend against consumer insects or attract insect predators.[24]

Fighting Power

Animals sometimes use jaws, beaks, teeth, hooves, horns, and claws as weapons. Carnivores use them as offensive weapons, or as defenses against other carnivores; herbivores use them to ward off carnivores or in competing with other members of their species for territory or mates.

When members of the same bird or mammal species fight, it is rarely to the death (this is not always the case with spiders and insects: female praying mantises devour their mates). Toucans, for example, use their giant beaks for sword-play, dueling with rivals; but one bird hardly ever seriously injures another.

When members of different species fight, the outcome is more often lethal. Predators, after all, depend on killing for their survival. They typically choose prey that are incapable of putting up much of a defense; but sometimes, if the prey animal is large enough (for example, a zebra being hunted by a lion), a battle ensues. If the prey is dispatched, predators of the same or different species may then fight over the carcass.

Some predator species (including wolves, lions, dolphins, and hyenas) often hunt in packs, attacking many prey (such as a herd of impala or a school of anchovies) at once. But warfare—in which many members of one group systematically attack another group of the same species—is rare; humans, ants, and chimpanzees provide the main observed instances. Some ants even raid colonies of other ant species to enslave their captives.

Plants fight, too, though usually not as photogenically as animals. There are over 500 species of carnivorous plants that use a variety of "trap" strategies to snare their prey (mostly insects). The main categories of such plants are: pitfall traps, which catch prey in a rolled leaf holding a pool of digestive enzymes; bladder traps, which create an internal vacuum to suck in prey; flypaper traps, which use glue to snare the feet of prey; snap traps, which use quick-moving leaves; and "lobster-pot traps," which force prey to move down a tunnel with inward-pointing hairs toward a digestive organ.

In addition (and more commonly), plants can give off chemicals that discourage insects and other predators, or outright poison them. Almond trees and sorghum stalks can release hydrogen cyanide as a defense; a cow munching on sorghum can be sickened as a result.

Many plants are able to chemically sense the presence of insect saliva, which causes the plant to quickly manufacture defensive chemicals.

Exclusionary and Territorial Power

Exclusionary power—the ability to prevent others from accessing resources—is the essence of competition, and it's common throughout nature.[25] It's seen in animals competing for foraging areas, mates, and nesting sites, and even in baby birds vying for their parents' attention during feeding. Exclusionary jostling occurs both among different species and among members of the same species.

Territoriality—the behavior of an animal in defining and defending its space for feeding or breeding—is a version of exclusionary behavior. I was recently reminded of it by some unusual activity around my bird feeder. Finches, nuthatches, and sparrows were gathering to feast, as usual, only to be chased away by an aggressive mockingbird—who didn't stay to eat. After a minute or two, a few of the smaller birds would return, only to be rousted again by the mocker. A little research revealed that my mockingbird's behavior, while unusual, is hardly unheard of: the little bully has somehow decided that the feeder is part of its territory, and, even though he's not much of a seed aficionado, he spends considerable time and effort making sure other birds stay away.

Territorial animals typically mark their territory using smells, calls, or visual signs. Defense of territory usually begins with the territorial defender confronting the interloper with ritualized aggression. Actual fighting, which could injure either or both animals, is typically a last resort.

Territoriality is seen in only a minority of species. And in the vast majority of those, exclusionary competition results in no injury (ants and chimpanzees, which sometimes fight to the death, provide exceptions to this rule). Territoriality and exclusionary power will take on a special significance in later chapters of this book, when we explore the origins of human behaviors related to private property and war—which have resulted in a great many injuries and deaths.

SIDEBAR 4

How Much Power?

It's interesting and helpful to have a sense of scale with regard to physical power. Here are some examples:

Nonhuman animals:

- **Mouse:** 0.8 watts, based on the daily energy expenditure of an average lab mouse.[26]
- **Horse:** 798.6 watts, based on the daily energy expenditure of a mid-sized horse.[27]
- **Elephant:** 2,292.4 watts, based on the daily energy expenditure of an average Asian elephant.[28]

Man-made systems:

- **A space shuttle taking off:** 1.2×10^{10} watts or 12 gigawatts, based on the combined power of solid rocket boosters and main engines.[29]
- **A wind turbine:** 2.43×10^{6} watts or 2.43 megawatts, based on the average rated capacity of new turbines.[30]
- **A solar panel:** 320 watts, based on the average new solar panel.[31]

Natural systems:

- **The Mississippi River at New Orleans:** 8.6×10^{7} watts or 86 megawatts, based on a calculation of kinetic energy using known average flow rate and an estimate of cross-sectional area made with known width and depth.[32]
- **A rainstorm over San Francisco:** 1 inch of rain over 3 hours: 6.4×10^{11} watts or 640 gigawatts; 1 inch of rain over 1 hour: 1.93×10^{12} watts or 1.93 terawatts; 2.5 inches of rain over 1 hour (as in a January 2017 rainstorm): 4.8×10^{12} watts or 4.8 terawatts, based on calculations of energy released through condensation using latent heat of condensation.[33]
- **A hurricane (category 3):** Total amount of energy released through condensation (cloud/rain) formation: 6×10^{14} watts. Energy dissipated by winds: 1.5×10^{12} watts.[34]

Humans:

- **A theoretical primate the size of a human, without fire or other human ways of gathering/amplifying power (just food, muscle):** 109.6 watts, based on average daily calorie expenditure of a hunter-gatherer.[35]
- **Hunter-gatherer, with fire and some tools:** 476 watts, based on average daily calorie expenditure of a hunter-gatherer and fire for cooking, heating, and tool-making. This number is highly variable depending on climate (hunter-gatherers in cold climates burn more wood for heating). This range would be approximately 272 watts in warm climates to watts to 1,625 watts in very cold climates.[36]
- **Early farmer with an ox:** 718 watts, based on average daily calorie expenditure of humans, oxen, and fire for cooking, heating, and tool-making. This too depends on the need for firewood as well as the number of draft animals per person—which is widely variable, but a 466 watt to 2,109 watt range can be approximated.[37]
- **An ancient king or pharaoh:** Up to a million watts, depending on the size of workforce commanded. If only personal direct food and fuel consumption is taken into account, the number would not be much higher than the upper end of early farmer range (718+ watts). However, if the human labor a ruler directs is included, the number is much higher. Take the example of Khufu, the Pharaoh believed to have commissioned the Great Pyramid of Giza. Archaeologists estimate that 4,000 laborers worked directly on the construction of the pyramid, and another 16,000–20,000 laborers provided supporting functions such as tool-making and food-preparation. Roughly 5,000 were likely permanent workers while the rest were temporary workers. We can estimate the energy output of the workforce on any given day. If there were 22,000 laborers burning an average of 1,000 kilocalories during working hours (caloric

expenditure was likely more for those doing construction and less for those providing supportive functions), this would amount to around 1 million watts.[38]

- **Modern industrial human, poor country (India):** 319 watts, based on per capita GDP and energy intensity of GDP; 812 watts, based on per capita energy consumption. The latter is likely more accurate. In India, a significant portion of the population uses wood cooking stoves, and this household use of biomass isn't accounted for in GDP.[39]
- **Modern industrial human, rich country (US):** 9,925 watts, based on per capita GDP and energy intensity of GDP; 9,024 watts based on per capita energy consumption. In this case, the GDP figure more accurately reflects US consumption. Since the US imports many energy-intensive products, counting only the energy used within the nation's borders can underestimate energy consumption.[40]
- **The human Superorganism (at its current size):** 1.84×10^{13} watts, calculated using 2018 primary energy consumption.[41]

Proto-Human Powers

The Power of Beauty and Attraction

Why do many animals—especially birds—put so much effort into breathtakingly beautiful displays of sound and color? Are the virtuosic songs and striking plumage of the males of many avian species simply signals to potential mates of their overall fitness? Or is more going on here? Charles Darwin, the father of evolutionary theory, believed the latter. The hunger for beauty, he argued, is an evolutionary force separate from natural selection, and sometimes on par with it in terms of its influence on the development of species.

Darwin's first book, *On the Origin of Species by Means of Natural Selection*, became a bible for evolutionary biologists. But his second book, *The Descent of Man, and Selection in Relation to Sex*, confounded many of his followers. In it, he described instance after instance where animals invest extraordinary effort in display activities. He wrote, “The sight of a feather in a peacock’s tail, whenever I gaze at it, makes me sick!” The feather is unquestionably beautiful, but its evolution is nearly impossible to explain in terms of fitness and natural selection. Why is nature so filled with apparently useless beauty?

Darwin’s solution to the conundrum was the principle of sexual selection. In species that reproduce through sex, the successful transmission of an individual’s genes to the next generation depends not just on that individual’s relative vigor, size, or strength (qualities we intuitively, though often mistakenly, associate with fitness), but also on its ability to attract a mate. Females of the species often choose males with whom to get it on (more rarely it’s the other way around), and the criteria for choosing or being chosen sometimes appear bizarre.

Most of his followers, rejecting this aspect of Darwin’s legacy, have attempted to explain these displays by hypothesizing natural selection benefits. But ornithologist Richard O. Prum, in *The Evolution of Beauty*, makes a convincing case that Darwin got it right in concluding that such displays often aren’t tied to objective measures of competitive fitness. “Individual organisms,” he writes, “wield the potential to evolve arbitrary and useless beauty completely independent of (and sometimes in opposition to) the forces of natural selection.”[42]

Consider the bowerbird of Australia. The adult male builds a bower (which is an elaborate structure that’s not a nest and has no other use) to attract a female. Various bowerbird species build differently sized and designed bowers; some carefully arrange colored objects—pebbles, petals, feathers, insects, bottlecaps—to decorate the structure. Why do these birds go to so much trouble? Meticulous research has shown that artistic effort on the part of the male, and selective preference on the part of the female, have coevolved in a self-reinforcing feedback process. In the male bowerbird, and many other creatures, the power to attract a mate has become inextricably tied to the activity of producing expressions of beauty that have no other practical value and are not signs of overall male fitness. Beauty has become a powerful end in itself. (In Chapter 2 we will explore how sexual selection and the power of beauty and attraction may have impacted human evolution as well.)

Evolutionary investments in display can proceed to such extremes that they lead to "aesthetic decadence," contributing to a species' decline and even extinction. When the males and females of a given species come to agree that only a particularly extravagant display—one whose costs impair the species' survival abilities—are worthy of mate choice, then attraction can truly become fatal. The fossil record probably holds plenty of examples, though teasing out the exact cause of extinction in any given case is often difficult (the Irish elk, with its impossibly bulky antlers, is probably a good example-candidate). It's perhaps easier to show instances of aesthetic decadence among creatures still living, such as the club-winged manakin, a small bird that lives in the Amazon rain forest. The male courts its potential mate by clapping his wings together at over 100 times per second, much faster than the flapping of a hummingbird's wings, producing an oboe-like tone. Females adore the sound and choose their mate based on the excellence of his wing-clapping performance. Unfortunately, however, in order to effectively make their unique sound, club-winged manakins need solid wing bones—which they have duly evolved. As a result, their flight is slow and clumsy, putting them at a distinct disadvantage compared to other birds.

Powers That Derive from Being a Specialist or a Generalist

Specialist species get better and better at exploiting a certain type of food within a specific environment. Perhaps the most famous example: when Darwin arrived on Galapagos Island in 1836, he found 15 species of finches, each of which had evolved a different form of beak for opening a particular kind of seed available on the island.

Generalists do many things, but are typically champions at none. Humans, crows, cockroaches, rats, and racoons are all generalists, and are able to eat a wide variety of animal and plant foods.[43]

Specialists have the advantage of being able to out-compete most other creatures that would otherwise take advantage of a targeted food source. The risk of specialization is that if the preferred food source is suddenly less abundant, the organism may have difficulty adapting. Generalists tend not to use any particular resource very efficiently. But, because they can harness a wider range of resources, generalists may have a power advantage in a varied, unpredictable, or rapidly changing environment.

There are fewer generalist than specialist species, but some generalists (such as crows and rats) are abundant and wide-ranging. One generalist species, *Homo sapiens*, has become especially abundant and wide-ranging, and hence collectively powerful, for reasons we will explore in the next three chapters.

The Power of Cooperation

Many of the powers we've been discussing are useful in competition—whether between one individual and another, or one species and another. However, evolution works not just by fierce competition, but also—perhaps even more so—by cooperation. Ironically, organisms that develop ways to cooperate often thereby derive a competitive advantage: working together, many individuals can become more powerful than they would be if working in isolation.

Nature offers innumerable examples of cooperative behavior; indeed, without it, there would be no multicellular organisms. We've already seen how eukaryotes are the result of an ancient symbiosis between two very different kinds of cells. Green plants—containing both mitochondria and chloroplasts—are double symbionts.

At the macro scale, cooperation among members of the same species is seen in ants, honey bees, fish that "school" (such as herring), prairie dogs, members of the canine family, many bird species, and all primates (this is only a partial list).

Cooperation between members of different species is also common. Many flowering plant species have evolved cooperative relationships with specific pollinators, in which both participants benefit. Sometimes smaller animals work out cooperative relationships with larger ones—such as cleaner fish (including cleaner wrasses, neon gobies, and some catfish) that feed on dead skin and parasites on larger predatory fish that could easily eat the cleaners, but don't.

You needn't go far to observe interspecies cooperation; indeed, each of us is host to trillions of microbes, including about a thousand different bacterial species (like our old friend *E. coli*), that live in and on the human body. Their total number is typically greater than the number of strictly human cells in our bodies. These various kinds of microorganisms generally complement each other and their host, fulfilling functions essential to life, including synthesizing vitamins and neurochemicals, aiding digestion, and strengthening the immune system.

Extreme cooperation can lead to extreme power. Ants, the most cooperative organisms on the planet until civilized humans came along, are one of the most successful groups in evolutionary history and account for about a third of all insect biomass. Humans, because they are extraordinarily cooperative, are able *individually* to specialize to an astonishing degree (especially so since the adoption of agriculture, as we will see in Chapter 3), thereby enabling *Homo sapiens* to take advantage of both generalist and specialist strategies to an extent unmatched elsewhere in nature.

Tool Power

Animals and plants obtain and exert many of their powers by developing parts of themselves for a particular purpose—such as a wing ideal for soaring on wind currents, or a tail perfect for swinging from tree branches. One way of understanding tools is to think of them as detachable organs. Since tools are not part of the organism and can be replaced or modified at will, an organism can use different tools for different purposes.

Decades ago, most scientists thought that the ability to make and use tools was uniquely human, but this attitude has gradually changed. Researchers were initially curious to see if other primates used tools. Chimps, for example, were observed to have specialized tool kits for hunting ants. Gorillas use tools less frequently than chimps and bonobos (perhaps because gorillas live in environments with an abundance of food plants), but they have been seen using sticks to gauge the depth of water.

However, nonhuman primates may not be the best examples of animal tool users. Crows have been observed modifying twigs, leaves, and their own feathers to serve as tools. In carefully designed experiments, crows have even figured out how to drop stones into pitchers to raise the level of water inside.

Other avian tool users include finches and woodpeckers, which have been seen to insert twigs into trees in order to catch or impale larvae. Several parrot species have been observed using tools to wedge open nuts they're trying to crack, or to scratch the backs of their heads. One parrot species, the palm cockatoo, occasionally fashions a drumstick from a tree branch, then strikes it repeatedly against a hollow tree trunk to make a distinctive sound that can be heard for miles. Biologists are still unsure of the purpose of this remarkable behavior.

Bottlenose dolphins in Shark Bay, Australia, carry marine sponges in their beaks to stir the sand on the ocean floor to uncover prey. It's said that they spend more time hunting with tools than any other nonhuman animal.

One could argue that a spider's web is a tool. The spider uses its spinneret glands to produce silk, which it then weaves into a web for catching unwary insects. The process by which spiders make their webs, and the designs they use, are instinctual and genetically coded. Yet each spider must make many decisions to creatively solve unique problems. And among spiders of the same species, some are clearly better than others at building and managing their webs. The net-casting spider weaves a small net, attaches it to its front legs, then waits for potential prey. When the victim arrives, the spider lunges forward to wrap the net around it, then bites and paralyzes its prey. Observed in any mammal, similar behavior would almost certainly be described as the making and use of a tool.

Prior to the appearance of humans and close human ancestors and relatives, toolmaking and tool use already existed in nature. But tools clearly represented an enormous opportunity for the further harnessing and leveraging of power, and also helped open the way to a different and much faster kind of evolution—cultural evolution—

which we'll discuss at more length when we get around to exploring language (in Chapter 3).[44]

Fire Power

The controlled use of fire constitutes a special instance of tool usage. Until recently, it was commonly thought that only humans had harnessed fire, but this is not strictly true. At least three Australian raptor species (the black kite, the whistling kite, and the brown falcon) have been observed to pick up burning twigs or branches from wildfires and then drop them at a distance, deliberately starting fires elsewhere in order to flush prey from undergrowth.

Still, the ability to harness fire is so rare in the nonhuman world that it might hardly be worth mentioning, except that it serves to put into perspective the vastly greater power ramifications that fire has had as result of human beings' ability to control it. We will unpack some of those implications in chapters 2, 4, and 5.

Trade-Offs of Specialization

As we've seen, organisms have developed amazing abilities. Why isn't every organism good at everything? Because getting really good at one thing tends to hamper your ability to do something else. To put it more formally, the extreme expression of any given trait is likely to reduce fitness in some way. The giraffe's long neck enables it to browse on the leaves of trees, but makes it highly vulnerable to predators when it needs to bow low to drink water. A bacterial mutation that confers resistance to an antibiotic may weaken the bacteria if that antibiotic isn't present. The bat can hear certain frequencies with extraordinary acuity, but if it simultaneously had the eyesight of a hawk, the ability to sense infrared radiation the way a pit viper does, and the ability to see ultraviolet colors the way many birds do, its brain would have to be very large and would likely be overloaded with stimuli.

Generally, if the benefits of an extreme specialization outweigh the costs and the organism is able to survive and reproduce, the extreme ability will be preserved; if the costs outweigh the benefits, evolution will de-emphasize the specialization or the organism will fade away and evolution will move on.

All of this suggests there are probably downsides to humans' specialized powers (extreme intelligence, a highly developed ability to communicate, and proficient tool use). We humans tend to emphasize the advantages of these traits, but it's always important to look for hidden costs. We'll be discussing these evolutionary costs at some length in later chapters.

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In short, prior to the appearance of humans, the natural world was already a complex system of powers and power balances. Energy originating in our nearest star was being cycled and recycled in intricate and beautiful ways via biochemical processes in individual cells—processes that enabled the flourishing of both single-celled and multicelled creatures, and ecosystems of unfathomable complexity.

Into this milieu came a handy animal, a generalist *and* a specialist, that was able to use many different powers in increasingly effective ways—and able, as we will see, to develop many powers (motion, perception, cognition, deception, communication, exclusion, cooperation, fighting, toolmaking, and control of fire) to extraordinary degrees.