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The Uses and Misuses of Human Cloning

SuperCooperators

Altruism, Evolution, and Why We Need Each Other to Succeed

Martin A. Nowak

with Roger Highfield

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The only thing that will redeem mankind is cooperation.
—BERTRAND RUSSELL

PREFACE

The Struggle

From the war of nature, from famine and death, the most exalted object which we are capable of conceiving, namely, the production of the higher animals, directly follows.

—Charles Darwin, *On the Origin of Species*

Biology has a dark side. Charles Darwin referred to this shadowy aspect of nature as the struggle for existence. He realized that competition is at the very heart of evolution. The fittest win this endless "struggle for life most severe" and all others perish. In consequence, every creature that crawls, swims, and flies today has ancestors that once successfully thrived and reproduced more often than their unfortunate competitors. As for the rest, they forfeited any chance to contribute to the next generation. They lost, and now they're gone.

The struggle was born at least 4 billion years ago, with the first primitive cells. They were simple bacteria, each one little more than a tiny, organized collection of chemicals. If one of these chemical machines had an advantage over its peers, it would reproduce faster. Given better-than-average access to a limited food source, it would prosper and its rivals perish. This struggle continues, and across a spectrum of habitats. Today, Earth is the planet of the cell. Microorganisms now teem in almost every habitat, from poles to deserts to geysers, rocks, and the inky depths of the oceans. Even in our own bodies, bacterial cells outnumber our own. When adding up the total number of cells on Earth today—around 10 to the power of 30, or 1 followed by 30 zeroes—all you have to do is estimate the number of bacterial cells; the rest is pocket change.

The struggle can also be found in those organized collections of cells that we call animals. On the African savannah, a lion crouches in the long grass, muscles tensed and senses tightly focused on a nearby herd. Slowly and silently it stalks the antelope and then suddenly, in a burst of speed, sprints toward an animal, leaps, grabs its neck, and pierces the skin, blood vessels, and windpipe with its long, sharp teeth. It drags the prey to the ground and holds tight until the antelope breathes its last. When the lion finishes with its kill, a shroud of vultures wraps the bloody remains.

In *The Descent of Man,* Darwin remarked that modern man was born of the same struggle on the same continent. "Africa was formerly inhabited by extinct apes closely allied to the gorilla and chimpanzee; and as these two species are now man's nearest allies, it is more probable that our early progenitors lived on the African continent than elsewhere." Our ancestors spread out to colonize the Earth during the last 60,000 years or so, outcompeting archaic species such as *Homo erectus* and the big-brained Neanderthals (though if you are European, Asian, or New Guinean, you may have a trace of Neanderthal blood racing through your veins). The struggle for existence continues apace, from competition between supermarkets to drive down prices to cutthroat rivalry between Wall Street firms.

In the game of life we are all driven by the struggle to succeed. We all want to be winners. There is the honest way to achieve this objective. Run faster than the pack. Jump higher. See farther. Think harder. Do better. But, as ever, there is the dark side, the calculating logic of self-interest that dictates that one should never help a competitor. In fact, why not go further and make life harder for your rivals? Why not cheat and deceive them too? There's the baker who palms you off with a stale loaf, rather than the one fresh out of the oven. There's the waiter who asks for a tip when the restaurant has already added a service charge. There's the pharmacist who recommends a well-known brand, when you can get a generic version of the same drug much more cheaply. Nice guys finish last, after all.

Humans are the selfish apes. We're the creatures who shun the needs of others. We're egocentrics, mercenaries, and narcissists. We look after number one. We are motivated by self-interest alone, down to every last bone in our bodies. Even our genes are said to be selfish. Yet competition does not tell the whole story of biology. Something profound is missing.

Creatures of every persuasion and level of complexity cooperate to live. Some of the earliest bacteria formed strings, where certain cells in each living filament die to nourish their neighbors with nitrogen. Some bacteria hunt in groups, much as a pride of lions hunt together to corner an antelope; ants form societies of millions of individuals that can solve complex problems, from farming to architecture to navigation; bees tirelessly harvest pollen for the good of the hive; mole rats generously allow their peers to dine on their droppings, providing a delicious second chance to digest fibrous roots; and meerkats risk their lives to guard a communal nest.

Human society fizzes with cooperation. Even the simplest things that we do involve more cooperation than you might think. Consider, for example, stopping at a coffee shop one morning to have a cappuccino and croissant for breakfast. To enjoy that simple pleasure could draw on the labors of a small army of people from at least half a dozen countries.

Farmers in Colombia grew the beans. Brazil provided the lush green fields of swaying sugar cane that was used to sweeten the beverage. The dash of creamy milk came from cows on a local farm and was heated with the help of electricity generated by a nuclear power station in a neighboring state. The barista, being a pretentious sort of fellow, made the coffee with mineral water from Fiji. As for that flaky croissant, the flour came from Canada, the butter from France, and the eggs from a local cooperative. The pastry was heated and browned in a Chinese-made oven. Many more people worked in supply lines that straddle the planet to bring these staples together.

Delivering that hot coffee and croissant also relied on a vast number of ideas, which have been widely disseminated by the remarkable medium of language. The result is a tightly woven network of cooperation stretching across the generations, as great ideas are generated, passed on, used, and embellished, from the first person to drink a beverage based on roasted seeds to the invention of the light bulb that illuminates the coffee shop, to the patenting of the first espresso machine.

The result, that simple everyday breakfast, is an astonishing cooperative feat that straddles both space and time. That little meal relies on concepts and ideas and inventions that have been passed down and around among vast numbers of people over hundreds, even thousands of years. The modern world is an extraordinary collective enterprise. The knowledge of how to select beans, make flour, build ovens, and froth milk is splintered in hundreds of heads. Today, the extent to which our brains collaborate matters as much as the size of our brains.

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This is the bright side of biology. The range and the extent to which we work together make us supreme cooperators, the greatest in the known universe. In this respect, our close relatives don't even come close. Take four hundred chimpanzees and put them in economy class on a seven-hour flight. They would, in all likelihood, stumble off the plane at their destination with bitten ears, missing fur, and bleeding limbs. Yet millions of us tolerate being crammed together this way so we can roam about the planet.

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Our breathtaking ability to cooperate is one of the main reasons we have managed to survive in every ecosystem on Earth, from scorched, sun-baked deserts to the frozen wastes of Antarctica to the dark, crushing ocean depths. Our remarkable ability to join forces has enabled us to take the first steps in a grand venture to leave the confines of our atmosphere and voyage toward the moon and the stars beyond.

By *cooperation,* I mean more than simply working toward a common aim. I mean something more specific, that would-be competitors decide to aid each other instead. This does not seem to make sense when viewed from a traditional Darwinian perspective. By helping another, a competitor hurts its own fitness—its rate of reproduction—or simply blunts its competitive edge. Yet it is easy to think of examples: a friend drives you to the dentist though it makes her late for work; you donate fifty dollars to charity rather than spending it on yourself. The cells in your body, rather than reproduce willy nilly to selfishly expand

would-be competitors
decide instead to aid each other

their own numbers, respect the greater needs of the body and multiply in an orderly fashion to create the kidney, the liver, the heart, and other vital organs.

Many everyday situations can be viewed as choices about whether or not to cooperate. Let's say you want to open a savings account with a British bank (as we discovered in *Mary Poppins,* which appeared long before the credit crunch, "a British bank is run with precision"). Imagine that you are standing at the counter as a smiling clerk patiently explains the various options on offer. Banks like to confuse their customers by offering a large number of accounts that differ in terms of fees, interest rates, access, and conditions. If you ask for the best interest rate, the clerk can interpret this apparently simple question in two ways. From his point of view, the best interest rate is the most meager and restrictive, the one that earns the bank the maximum profit. From the customer's point of view, the best rate is the one that earns the most money. If the clerk offers the former, that is an example of defection. But if he recommends an account that gives you, and not the bank, the maximum return, that is an example of cooperation.

Once cooperation is expressed in this way, it seems amazing. Why weaken your own fitness to increase the fitness of a competitor? Why bother to look after anyone besides number one? Cooperation goes against the grain of self-interest. Cooperation is irrational. From the perspective of Darwin's formulation for the struggle for existence, it makes no sense to aid a potential rival, yet there is evidence that this occurs among even the lowliest creatures. When one bacterium goes to the trouble of making an enzyme to digest its food, it is helping to feed neighboring cells too—rivals in the struggle to survive.

This looks like a fatal anomaly in the great scheme of life. Natural selection should lead animals to behave in ways that increase their own chances of survival and reproduction, not improve the fortunes of others. In the never-ending scrabble for food, territory, and mates in evolution, why would one individual ever bother to go out of its way to help another?

BEYOND COOPERATION

We are all dependent on one another, every soul of us on earth.

—George Bernard Shaw, *Pygmalion*

Scientists from a wide range of disciplines have attempted for more than a century to explain how cooperation, altruism, and self-sacrifice arose in our dog-eat-dog world. Darwin himself was troubled by selfless behavior. Yet in his great works, the problem of cooperation was a sideshow, a detail that had to be explained away. That attitude prevails among many biologists even today.

In stark contrast, I believe that our ability to cooperate goes hand in hand with succeeding in the struggle to survive, as surmised more than a century ago by Peter Kropotkin (1842–1921), the Russian prince and anarchist communist who believed that a society freed from the shackles of government would thrive on communal enterprise. In *Mutual Aid* (1902), Kropotkin wrote: "Besides *the law of Mutual Struggle* there is in Nature *the law of Mutual Aid,* which, for the success of the struggle for life, and especially for the progressive evolution of the species, is far more important than the law of mutual contest. This suggestion . . . was, in reality, nothing but a further development of the ideas expressed by Darwin himself."

I have spent more than two decades cooperating with many great minds to solve the mystery of how natural selection can lead to mutual aid, so that competition turns into cooperation. I have introduced some new ideas to this well-explored field and refined this mix with my own specialty, which relies on blending mathematics and biology. My studies show that cooperation is entirely compatible with the hard-boiled arithmetic of survival in an unremittingly cold-eyed and competitive environment. Based on mathematical insights, I have created idealized communities in a computer and charted the conditions in which cooperation can take hold and bloom. My confidence in what I have found has been bolstered by research on a wide range of species, from bugs to people. In light of all this work, I have now pinned down

Pursuing the snuggle for existence

five basic mechanisms of cooperation. The way that we human beings collaborate is as clearly described by mathematics as the descent of the apple that once fell in Newton's garden.

These mechanisms tell us much about the way the world works. They reveal, for example, that your big brain evolved to cope with gossip, not the other way around; that your guts have cone-like glands to fend off that potentially deadly breakdown of cellular cooperation that we know as cancer; that you are more generous if you sense that you are being watched (even if you are not); that the fewer friends you have, the more strongly your fate is bound to theirs; genes may not be that selfish, after all; if you are a cooperator, you will find yourself surrounded by other cooperators so that what you reap is what you sow; no matter what we do, empires will always decline and fall; and to succeed in life, you need to work together—pursuing the snuggle for existence, if you like—just as much as you strive to win the struggle for existence. In this way, the quest to understand cooperation has enabled us to capture the essence of all kinds of living, breathing, red-blooded evolving processes.

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Cooperation—not competition—underpins innovation. To spur creativity, and to encourage people to come up with original ideas, you need to use the lure of the carrot, not fear of the stick. Cooperation is the architect of creativity throughout evolution, from cells to multicellular creatures to anthills to villages to cities. Without cooperation there can be neither construction nor complexity in evolution.

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I can derive everyday insights—as well as many unexpected ones—from mathematical and evolutionary models of cooperation. While the idea that the trajectory of spears, cannonballs, and planets can be traced out by equations is familiar, I find it extraordinary that we can also use mathematics to map out the trajectory of evolution. And, of course, it is one thing to know how to foster cooperation but it is quite another to explain why an action helps us get along with each other and to what extent. The mathematical exploration of these mechanisms enables us to do this with profound understanding and with precision too. This is proof, as if we need it, that math is universal.

In the following chapters I will explain the origins of each mechanism of cooperation and interweave this train of thought with my own intellectual journey, one that began in Vienna and then continued to Oxford, Princeton, and now Harvard. En route, I have had the honor to cooperate with many brilliant scientists and mathematicians. Two of them proved particularly inspirational: Karl Sigmund and Robert May, for reasons that will become clear. I have also had to enlist the help of computer programs, students willing to play games, and various funding bodies, from foundations to philanthropists. It is a lovely and intoxicating thought that a high degree of cooperation is required to understand cooperation. And to further underline this powerful idea, this book is also a feat of cooperation between Roger Highfield and myself.

The implications of this new understanding of cooperation are profound. Previously, there were only two basic principles of evolution—mutation and selection—where the former generates genetic diversity and the latter picks the individuals that are best suited to a given environment. For us to understand the creative aspects of evolution, we must now accept that cooperation is the third principle. For selection you need mutation and, in the same way, for cooperation you need both selection and mutation. From cooperation can emerge the constructive side of evolution, from genes to organisms to language and complex social behaviors. Cooperation is the master architect of evolution.

My work has also shown that cooperation always waxes and wanes. The degree to which individuals are able to cooperate rises and falls, like the great heartbeat of nature. That is why, even though we are extraordinary cooperators, human society has been—and always will be—riven with conflict. Global human cooperation now teeters on a threshold. The accelerating wealth and industry of Earth's increasing inhabitants—itself a triumph of cooperation—is exhausting the ability of our home planet to support us all. There's rising pressure on each of us to compete for the planet's dwindling resources.

Many problems that challenge us today can be traced back to a profound tension between what is good and desirable for society as a whole and what is good and desirable for an individual. That conflict can be found in global problems such as climate change, pollution, resource depletion, poverty, hunger, and overpopulation. The biggest issues of all—saving the planet and maximizing the collective lifetime of the species *Homo sapiens*—cannot be solved by technology alone. They require novel ways for us to work in harmony. If we are to continue to thrive, we have but one option. We now have to manage the planet as a whole. If we are to win the struggle for existence, and avoid a precipitous fall, there's no choice but to harness this extraordinary creative force. We now have to refine and to extend our ability to cooperate. We must become familiar with the science of cooperation. Now, more than ever, the world needs SuperCooperators.

Cooperation is the master architect of evolution.

The Science of Cooperation

(Isn't this an oxymoron? Science means "to cut" or "divide") world to understand how these mechanisms worked and what their wider implications were.

Some scientists regard the Prisoner's Dilemma as a remarkably revealing metaphor of biological behavior, evolution, and life. Others regard it as far too simple to take into account all the subtle forces at play in real societies and in biology. I agree with both camps. The Dilemma is not itself the key to understanding life. For the Dilemma to tell us something useful about the biological world, we need to place it in the context of evolution.

Evolution can only take place in populations of reproducing individuals. In these populations, mistakes in reproduction lead to mutation. The resulting mutants might reproduce at different rates, as one mutant does better in one environment than another. And reproduction at different rates leads to selection—the faster-reproducing individuals are selected and thrive. In this context we can think about the payouts of the Prisoner's Dilemma in terms of what evolutionary scientists call "fitness" (think of it as the rate of reproduction). Now we can express what cooperation in the Prisoner's Dilemma means when placed in an evolutionary context: if I help you then I lower my fitness and increase your fitness.

Here's where the story gets fascinating. Now that we have put the Dilemma in an evolutionary form, we discover that there is a fundamental problem. Natural selection actually opposes cooperation in a basic Prisoner's Dilemma. At its heart, natural selection undermines our ability to work together. Why is this? Because in what mathematicians call a well-mixed population, where any two individuals meet equally often, cooperators always have a lower fitness than defectors—they're always less likely to survive. As they die off, natural selection will slowly increase the number of defectors until all the cooperators have been exterminated. This is striking because a population consisting entirely of cooperators has a higher average fitness than a population made entirely of defectors. Natural selection actually destroys what would be best for the entire population. Natural selection undermines the greater good.

To favor cooperation, natural selection needs help in the form of mechanisms for the evolution of cooperation. We know such mechanisms exist because all around us is abundant evidence that it does pay to cooperate, from the towering termite mound to the stadium rock concert to the surge of commuters in and out of a city during a working day. In reality, evolution has used these various mechanisms to overcome the limitations of natural selection. Over the millennia they have shaped genetic evolution, in cells or microbes or animals. Nature smiles on cooperation.

These mechanisms of cooperation shape cultural evolution too, the patterns of change in how we behave, the things we wear, what we say, the art we produce, and so on. This aspect of evolution is more familiar: when we learn from each other and alter the way we act accordingly. It also takes place over much shorter timescales. Think about a population of humans in which people learn different strategies to cope with the world around them, whether religion or boat building or hammering a nail into a piece of wood. The impact of cooperation on culture is huge and, for me, the central reason why life is so beguiling and beautiful.

QUEST FOR THE EVOLUTION OF COOPERATION

> *Mathematics, rightly viewed, possesses not only truth, but supreme beauty—a beauty cold and austere, like that of sculpture, without appeal to any part of our weaker nature, without the gorgeous trappings of painting or music, yet sublimely pure, and capable of a stern perfection such as only the greatest art can show.*
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> —Bertrand Russell, *Study of Mathematics*

My overall approach to reveal and understand the mechanisms of cooperation is easy to explain, even if my detailed workings might appear mysterious. I like to take informal ideas, instincts, even impressions of life and render them into a mathematical form. Mathematics allows me to chisel down into messy, complicated issues and—with judgment and a little luck—reveal simplicity and grandeur beneath. At the heart of a successful mathematical model is a law of nature, an expression of truth that is capable of generating awe in the same way as Michelangelo's extraordinary sculptures, whose power to amaze comes from the truth they capture about physical beauty.

Legend has it that when asked how he had created David, his masterpiece, Michelangelo explained that he simply took away everything from the block of marble that was not David. A mathematician, when confronted by the awesome complexity of nature, also has to hack away at a wealth of observations and ideas until the very essence of the problem becomes clear, along with a mathematical idea of unparalleled beauty. Just as Michelangelo wanted his figures to break free from the stone that imprisoned them, so I want mathematical models to take on a life beyond my expectations, and work in circumstances other than those in which they were conceived.

Michelangelo sought inspiration from the human form, notably the male nude, and also from ideas such as Neoplatonism, a philosophy that regards the body as a vessel for a soul that longs to return to God. Over the few centuries that science has been trying to make sense of nature, the inspiration for mathematical representations of the world has changed. At first, the focus was more on understanding the physical world. Think of how Sir Isaac Newton used mathematics to make sense of motion, from the movement of the planets around the sun to the paths of arrows on their way to a target. To the amazement of many, Newton showed that bodies on Earth and in the majestic heavens were governed by one and the same force—gravity—even though planets are gripped in an orbit while objects like arrows and apples drop to the ground.

Today, the models of our cosmos are also concerned with biology and society. Among the eddies and ripples of that great river of ideas that has flowed down the generations to shape the ways in which scientists model these living aspects of the world are the powerful currents generated by Charles Darwin (1809–1882), who devised a unifying view of life's origins, a revolutionary insight that is still sending out shock waves today.

Darwin worked slowly and methodically, using his remarkable ability to make sense of painstaking studies he had conducted over decades, to conclude that all contemporary species have a common ancestry. He showed that the process of natural selection was the major mechanism of change in living things. Because reproduction is not a perfect form of replication, there is variation and with this diversity comes the potential to evolve. But equally, as the game of Chinese Whispers (also known as Gossip or Telephone) illustrates, without a way of selecting changes that are meaningful—a sentence that makes sense—the result is at best misleading and at worst a chaotic babble. Darwin came up with the idea that a trait will persist over many generations only if it confers an evolutionary advantage, and that powerful idea is now a basic tenet of science.

Darwin's message is simple and yet it helps to generate boundless complexity. There exists, within each and every creature, some information that can be passed from one generation to the next. Across a population, there is variation in this information. Because when there are limited resources and more individuals are born than can live or breed, there develops a struggle to stay alive and, just as important, to find a mate. In that struggle to survive, those individuals who bear certain traits (kinds of information) fail and are overtaken by others who are better suited to their environs. Such inherited differences in the ability to pass genes down the generations—natural selection—mean that advantageous forms become more common as the generations succeed. Only one thing counts: survival long enough to reproduce.

Darwin's theory to explain the diverse and ever-changing nature of life has been buttressed by an ever-increasing wealth of data accumulated by biologists. As time goes by, the action of selection in a given environment means that important differences can emerge during the course of evolution. As new variations accumulate, a lineage may become so different that it can no longer exchange genes with others that were once its kin. In this way, a new species is born. Intriguingly, although we now call this mechanism "evolution," the word itself does not appear in *The Origin of Species.*

Darwin himself was convinced that selection was ruled by conflict.

best adapted to an environment

He wrote endlessly about the "struggle for existence" all around us in nature. His theme took on a life of its own as it was taken up and embellished with gusto by many others. Nature is "red in tooth and claw," as Tennyson famously put it when recalling the death of a friend. The catchy term "survival of the fittest" was coined in 1864 by the philosopher Herbert Spencer, a champion of the free market, and this signaled the introduction of Darwinian thinking into the political arena too.

Natural selection is after all about competition, dog-eat-dog and winner takes all. But Darwin was of course talking about the species that was the best adapted to an environment, not necessarily the strongest. Still, one newspaper concluded that Darwin's work showed that "might is right & therefore that Napoleon is right & every cheating tradesman is also right." Darwin's thinking was increasingly abused to justify the likes of racism and genocide, to explain why white colonialists triumphed over "inferior" native races, to breed "superior" humans and so on. These abuses are, in a twisted and depressing way, a testament to the power of his ideas.

But, as I have already stressed, competition is far from being the whole story. We help each other. Sometimes we help strangers too. We do it on a global scale with charities such as Oxfam, which helps people in more than seventy countries, and the Bill & Melinda Gates Foundation, which supports work in more than one hundred nations. We do it elaborately, with expensive celebrity-laden fund-raising dinners in smart venues. We are also charitable to animals. Why? This may look like an evolutionary loose end. In fact it is absolutely central to the story of life.

When cast in an evolutionary form, the Prisoner's Dilemma shows us that competition and hence conflict are always present, just as yin always comes with yang. Darwin and most of those who have followed in his giant footsteps have talked about mutation and selection. But we need a third ingredient, cooperation, to create complex entities, from cells to societies. I have accumulated a wide range of evidence to show that competition can sometimes lead to cooperation. By understanding this, we can explain how cells, and multicellular organisms such as

We need cooperation to create complex entities

Cooperation is the architect of living complexity (restate) Q

people, evolved, and why they act in the complicated ways that they do in societies. Cooperation is the architect of living complexity.

To appreciate this, we first need to put evolution itself on a firmer foundation. Concepts such as mutation, selection, and fitness only become precise when bolted down in a mathematical form. Darwin himself did not do this, a shortcoming that he was only too aware of. In his autobiography, he confessed his own inability to do sums: "I have deeply regretted that I did not proceed far enough at least to understand something of the great leading principles of mathematics; for men thus endowed seem to have an extra sense." He seemed aware that more rigor was required to flesh out the implications of his radical ideas about life. He regarded his mind "as a machine for grinding general laws out of large collections of facts." But even Darwin yearned for a more "top down" approach, so he could conjure up more precise laws to explain a great mass of data. He needed a mathematical model.

The modern understanding of the process of inheritance is now called "Mendelian," in honor of Gregor Mendel, who had settled for being a monk after failing his botany exams at the University of Vienna. By sorting out the results of crossing round and wrinkly peas, Mendel revealed that inheritance is "particulate" rather than "blending." Offspring inherit individual instructions (genes) from their parents such that round and wrinkly parents produce either round or wrinkly offspring and not something in between. What is often overlooked in his story is that Mendel was a good student of mathematics. The great geneticist and statistician Sir Ronald Fisher went so far as to call him "a mathematician with an interest in biology." Mendel uncovered these rules of inheritance because he was motivated by a clear mathematical hypothesis, even to the extent of ignoring ambiguous results that did not fit. Had Mendel conducted an open-minded statistical analysis of his results, he might not have been successful.

A simple equation to show the effect of passing genes down the generations was found in 1908 by G. H. Hardy, a cricket-loving Cambridge mathematician who celebrated the artistry of his subject in his timeless book *A Mathematician's Apology*. In an unusual reversal of the usual roles, the work of this pure mathematician was generalized by the

German doctor Wilhelm Weinberg to show the incidence of genes in a population. Robert May (now Lord May of Oxford) once went so far as to call the Hardy-Weinberg law biology's equivalent of Newton's first law. Thanks to Hardy and Weinberg we now had a mathematical law that applied across a spectrum of living things.

This attempt to model how inheritance works in nature was extended in seminal investigations conducted in the 1920s and 1930s by a remarkable trio. First, Sir Ronald Fisher, whose extraordinary ability to visualize problems came from having to be tutored in mathematics as a child without the aid of paper and pen, due to his poor eyesight. There was also the mighty figure of J. B. S. Haldane, an aristocrat and Marxist who once edited the *Daily Worker*. I will return to Haldane in chapter 5. The last of this remarkable trio was Sewall Wright, an American geneticist who was fond of philosophy, that relative of mathematics (forgive me for cracking the old joke about the difference: while mathematicians need paper, pencil, and a wastepaper basket, philosophers need only paper and pencil).

Together, this threesome put the fundamental concepts of evolution, selection, and mutation in a mathematical framework for the first time: they blended Darwin's emphasis on individual animals competing to sire the next generation with Mendel's studies of how distinct genetic traits are passed down from parent to offspring, a combination now generally referred to as the synthetic view of evolution, the modern synthesis, or neo-Darwinian. With many others, I have also extended these ideas by looking at the Prisoner's Dilemma in evolving populations to come up with the basic mechanisms that explain how cooperation can thrive in a Darwinian dog-eat-dog world.

Over the years I have explored the Dilemma, using computer models, mathematics, and experiments to reveal how cooperation can evolve and how it is woven into the very fabric of the cosmos. In all there are five mechanisms that lead to cooperation. I will discuss each one of them in the next five chapters and then, in the remainder of the book, show how they offer novel insights into a diverse range of issues, stretching from straightforward feats of molecular cooperation to the many and intricate forms of human cooperation.

Cooperation is woven into the very fabric of the cosmos

I will examine the processes that paved the way to the emergence of the first living things and the extraordinary feats of cooperation that led to multicellular organisms, along with how cellular cooperation can go awry and lead to cancer. I will outline a new theory to account for the tremendous amount of cooperation seen in the advanced social behavior of insects. I will move on to discuss language and how it evolved to be the glue that binds much of human cooperation; the "public goods" game, the biggest challenge to cooperation today; the role of punishment; and then networks, whether of friends or acquaintances, and the extraordinary insights into cooperation that come from studying them. Humans are SuperCooperators. We can draw on all the mechanisms of cooperation that I will discuss in the following pages, thanks in large part to our dazzling powers of language and communication. I also hope to explain why I have come to the conclusion that although human beings are the dominant cooperators on Earth, man has no alternative but to evolve further, with the help of the extraordinary degree of control that we now exert over the modern environment. This next step in our evolution is necessary because we face serious global issues, many of which boil down to a fundamental question of survival. We are now so powerful that we could destroy ourselves. We need to harness the creative power of cooperation in novel ways.

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