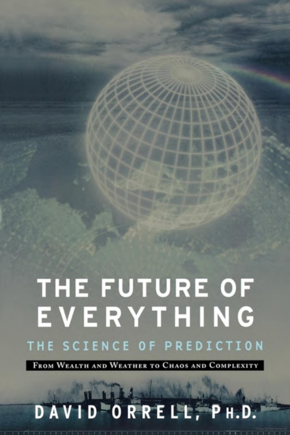

THE FUTURE OF EVERYTHING

THE SCIENCE OF PREDICTION

FROM WEALTH AND WEATHER TO CHAOS AND COMPLEXITY

DAVID ORRELL, PH.D.

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THUNDER'S MOUTH PRESS
NEW YORK

THE FUTURE OF EVERYTHING
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Published in the United States by
Thunder's Mouth Press
An Imprint of Avalon Publishing Group, Inc.
245 West 17th Street, 11th Floor
New York, NY 10011
www.thundersmouth.com

AVALON

This U.S. edition published by arrangement with HarperCollins Publishers Ltd., Toronto, Canada

First Thunder's Mouth Press edition, January 2007

Library of Congress Cataloging-in-Publication Data is available.

ISBN-10: 1-56858-369-9
ISBN-13: 978-1-56858-369-3

9 8 7 6 5 4 3 2 1

Printed in the United States of America
Distributed by Publishers Group West

CONTENTS

PAST

PRESENT

FUTURE

► INTRODUCTION

THE SCIENCE AND SOCIOLOGY OF FORECASTING

The term "natural disaster" has become an increasingly anachronistic misnomer. In reality, human behavior transforms natural hazards into what should really be called unnatural disasters.

—Kofi Annan, Secretary-General of the United Nations

Prediction is very difficult, especially if it's about the future.

—Niels Bohr, Nobel laureate in physics

ANATOMY OF A STORM

By December 15, 1999, the run-up to the new millennium had begun in earnest. People around the world were getting the champagne in, ready to uncork it the moment 1/1/2000 did its giant, slow march into their time zone. The NASDAQ stock-market index was also acquiring a champagne-like froth, as the Internet rewrote the rules of the world economy. The only cloud on the horizon—a potential storm—was the Millennium Bug, a software error caused when programmers rounded off the computer's internal date from four digits to two. Many predicted it would bring chaos, or even collapse, to the world economy.

In the slums, or *ranchos,* perched high on El Avila mountain north of Caracas, Venezuela, the Millennium Bug was not a major worry. Most of the residents had electricity, acquired by tapping illegally into the network, but Internet access was limited, to say the least. They were more excited about that day's referendum, which their hero, the new president, Hugo Chavez, had called to get the constitution approved. Voter turnout was high, and 78 percent in favour, despite the heavy rains, which had been falling for days and seemed to be getting worse.

Normally, the rainy season lasted only until October, but this year was an exception. The weather was out of synch. Some in the government suggested that the more vulnerable areas of Caracas be evacuated, in case the steep slopes became unstable. Perhaps not wishing to disrupt the referendum, however, the government took no action.

Early the next morning, December 16, the northern side of El Avila, which faces the coastal resorts near the airport, simply gave way. Witnesses said that huge waves of water, six metres high, cascaded down the mountain, carrying away everything in their wake—trees, cars, houses, people. Giant boulders hurtled down narrow gullies, not stopping until they fell into the ocean or smashed into the luxury apartment blocks that lined the coast. One survivor, a young woman, described waking up in the middle of the night to the sound of the water and the rocks crashing down the mountain and people yelling, "The river is coming!"[1] The water filled half her house before she could get out the door. Many others weren't so lucky.

At first, the scale of the disaster was not comprehended. Estimates were for 100 dead, then 500. By December 22, this had grown to 30,000, with perhaps ten times that many left homeless. Many of the bodies were swept out to sea or buried under the mud, and were impossible to recover. Survivors gathered in halls and stadiums, desperately searching for lost relatives. Rescue workers were completely overwhelmed. One told a journalist from the *Independent* how he had rescued a three-year-old girl: "Every time she saw water, she screamed."[2] Many feared that the lack of drinking water and sanitation would lead to disease outbreaks, magnifying the human impact, but fortunately this did not come to pass.

Almost immediately, the storm was politicized. The president's opponents castigated him for proceeding with the referendum. On Christmas Day, Chavez distributed gifts to hundreds of orphaned children at the Poliedro sports arena, in Caracas. When a reporter suggested the ex-paratrooper was culpable for the disaster, he replied: "They should shoot me if I have any personal responsibility in this."[3]

Could this storm, with all of its social, economic, and medical repercussions, have been predicted? Was it a random, unforeseeable event, or was someone responsible? How about the weather forecasters? The conditions for the storm began to develop in early December, when a cold front encountered a southwesterly flow of moist air, resulting in precipitation over the northern coast. There was one week of moderate rain, followed by two days of extremely heavy rain on December 15 and 16. The daily totals recorded at the nearby Maiquetia International Airport for these days were so excessive that, in theory, they wouldn't be repeated for 1,000 years—truly a millennial storm.[4] Almost by definition, such events do not get predicted; no forecaster likes to predict something he has never seen happen.

High above the storm, watching it develop, was a GOES 8 satellite belonging to the National Oceanic and Atmospheric Administration. Its mechanical infrared eye didn't pick up the horror on the ground; it was focused on the cloud-tops, taking temperature readings that could be used to estimate rainfall. However, the relatively coarse resolution—the smallest features it could detect were roughly four kilometres by four kilometres—meant that it could only confirm the location of the maximum rainfall.[5] The storm seemed to stand still, as if it was intent on bringing the mountain down.

Even with the amount of rain, though, no one could have foreseen the scale of the mudslides. And if they had, no one would have paid attention. As a forecaster at the National Hurricane Center in Miami admitted, for every mudslide they got right, they were "going to end up screaming wolf maybe 10 times."[6] The instability of the soil was the result of a number of factors, not all of them natural. The poor *rancho* areas were completely unregulated by the government; in fact, because of high levels of crime, many were no-go zones for the police.[7] Much of the forested land around the hills had been clear-cut by residents for firewood and construction material or cut down by private companies, weakening the soil. Benches had been cut into the steep hillsides to support the houses of cinder block and corrugated iron, further destabilizing the ground. Many of the homes were situated in dry riverbeds, so were directly in the path of the mudslide as it coursed down the gullies.

In fact, the disaster was caused by a range of complex, intertwined forces. Historical records from Spanish archives show that major floods and landslides are hardly new to the area.[8] Casualties were so high this time because of the sheer number of people—around 3 million—who now make their homes on the highly inhospitable mountains clustered around Caracas. This is a result not of extreme weather but of extreme disparities in wealth and migration to overpopulated urban areas. The storm, and its unusual timing, might also have been influenced by global warming, which in turn depends on the amount of carbon dioxide emitted from the world economy. Warmer oceans mean more water gets evaporated, so storms are expected to become more powerful.[9] The stakes for forecasters may grow higher still.

When I visited the flood area a year later, it was still covered in a layer of light brown soil. Since it was impossible to recover bodies, some of which were buried six metres down or more, the Catholic priests consecrated the entire place as a burial site. Already, though, the *ranchos* are encroaching on the territory they lost. Was it really a once-in-a-millennium event, or will the same thing happen again in the next hundred years? Or the next ten?

MAPPING THE FUTURE

The Future of Everything is about scientific prediction in the areas of weather, health, and wealth—how we foresee storms or fair weather, sickness or health, booms or crashes. It might seem that forecasts of the atmosphere have little to do with prediction of diseases or the economy, but in fact these three areas are closely linked. For one thing, they often affect each other, so prediction is an intrinsically holistic business. As shown above, a storm's impact depends on the conditions on the ground, and can have huge economic consequences. When Hurricane Katrina swung into the Gulf coast in late August 2005, flooding much of New Orleans and knocking out oil refineries, its financial impact was greater than that of the 9/11 terrorist attacks. In 2003, for Toronto, Hong Kong, and other cities, the storm was called SARS. Global warming too is a multistranded problem with complex repercussions. Like a potentially larger version of the Caracas storm, it exists at the centre of a vortex of social and environmental causes and effects. Atmospheric carbon dioxide is influenced by economic output and population levels; the resulting climate shifts and environmental stress may affect the spread of disease; large-scale epidemics have in the past severely disrupted economic activity; and so on.

The three types of prediction also use similar methods and share a common past. A traditional technique is astrology, which links the biological event of a baby's birth or the atmospheric and economic event of good harvest weather to the motion of the planets. Many people begin their day by reading their horoscope in the newspaper. Because I'm a Gemini (and therefore conflicted), I read my horoscope occasionally but never believe it. However, I will gladly check the five-day, long-range weather forecast, which probably has a lower accuracy rate.

For much of history, the same experts supplied both horoscopes and weather forecasts; humans and the atmosphere danced to the same tune. The seventeenth-century astronomer Johannes Kepler paid his way through university, and indeed much of the rest of his life, this way. Even now, when we talk about the weather, we often describe it in almost human terms. It is a cheerful day or a gloomy one; a storm is violent; a hurricane has a mind—and always a name—of its own. The weather is a character in all our lives, and sometimes it is a criminal.

The first newspaper weather map appeared on April 1, 1875, in *The Times* of London. It was prepared by the British scientist Sir Francis Galton, who also discovered the anti-cyclone.[10] Three years later, Galton gave a lecture at London's Anthropological Institute on a rather different subject. He presented composite photographs of the faces of prison convicts, dividing them into three groups by the type of offence. His aim was to search for common characteristics within each group. Influenced and inspired by the ideas of his cousin, Charles Darwin, Galton believed that traits such as "eminence" and criminality were inherited and linked to physical appearance. Just as he had scanned weather maps for patterns that would foretell a coming storm, he now looked for facial characteristics that warned of criminality. To help bring out such features, he made the composite pictures, which overlaid the faces of up to eight individuals.[11] The results were not very useful for prediction. What they showed was more a common humanity than any particular demonic trait. (As discussed in Chapter 5, this didn't prevent Galton from inventing the field of eugenics to "improve" the human race.)

Since Galton's time, a huge scientific effort has been devoted to looking into our future weather, health, and wealth, now using mathematical models. These emulate the flow of air and water in the atmosphere, or substances in our body, or money in the economy, using large sets of equations. Although the calculations are performed on high-speed computers, the techniques are essentially the same as those first developed by physicists such as Isaac Newton to study the dynamics of celestial objects. Like astrology, our predictive models of the future have their roots in the stars.

Weather prediction has evolved in the past half century into the multi-billion-dollar business of providing up-to-the-minute forecasts to the media and to weather-affected industries, such as agriculture, transport, and insurance. In biology, the Human Genome Project catalogued all human genes in a kind of giant library of our species; one of the stated aims was the prediction and control of genetic traits and diseases. Perhaps the greatest preoccupation of predictors has been the infinitely intriguing motions of the trillion-dollar financial markets. Companies, governments, and universities around the world, as well as giant institutions like the International Monetary Fund and the World Bank, hire thousands of economists in an effort to foresee economic events.

It turns out, though, that predictions of weather, health, and wealth have another thing in common. While scientists have had great success in squinting through microscopes at the smallest forms of life, or smashing atoms together in giant particle accelerators to analyze the structure of matter, or using telescopes to look forwards in space and backwards in time at the formation of distant galaxies, their visions into the future have been, like Galton's composite photographs, blurred and murky. As a result, projections tend to go astray.

In weather forecasting, for example, accuracy has improved in a slow, iterative manner, but if you're not a natural risk-taker, you should put little faith in a five-day forecast. We can put a man on the moon, but timing a shuttle landing around the weather is still tricky. In medicine, biologists have realized that the connection between genes and traits is not a straight line but a highly twisted and circuitous one. It is frequently announced in the press that the gene that causes some condition has been discovered, only for the news to fade from public attention as the complexities emerge. And in economics, the dominant "efficient market" theory, which has been weirdly embraced by many highly paid predictors, says that, in principle, the economy cannot be predicted. The best one can do is predict and control financial risk. Even this aim seems out of reach after events like the Black Monday crash in 1987 or the bursting of the Internet bubble.

The reason scientists—who are usually not closet Nostradamuses—have been drawn to making predictions in these areas (rather than, say, fashion or popular music) is because the underlying systems seem quantifiable and computationally tractable. Weather is just fluid flow, the human body is biochemistry, the economy is money. So what is going wrong? What do these systems have that escapes the models? Is our difficulty in forecasting the future health of the planet related to our difficulty in predicting the health of our own body? Or the health of the economy? Will we always be blind to the future, reacting impulsively to the next crisis or piece of good fortune when it comes along? Finding the answers to these questions is the target of *The Future of Everything*.

DON'T BLAME THE BUTTERFLY

My own introduction to predictability occurred when I returned to university, after several years as a jobbing mathematician, to do a Ph.D. on model error in weather forecasting. Model error represents the difference between the model—typically a set of mathematical equations based on physical "laws"—and the actual system it is supposed to emulate. For example, the trajectory of an arrow is something that can be determined reasonably accurately from the arrow's starting position and its velocity—the initial conditions—using the laws of physics. But if there's a gust of wind that is not included in the model, then the arrow will depart slightly from its predicted path. That's model error. It might not be important, unless you happen to be the person waiting at the other end with the apple on your head.

In weather forecasting, there had been little investigation of model error, despite the fact that even forecasters agreed that predictions usually missed their target after about two or three days. From my work experience (by which I mean glaring discrepancies between my calculations and reality), I knew that even engineered systems, where all the forces and material properties are exactly known, could still be hard to model accurately. The atmosphere was a horrendously complex system in comparison, so model error should have been huge. However, the dominant theory was that forecasts went wrong not because of any deficiency in the model, but because small errors in the initial condition were magnified by chaos—the so-called butterfly effect. Storms like the one that hit the north coast of Venezuela could, in principle, be caused by an insect flapping its wings somewhere on the other side of the world.

My work over the next couple of years was aimed at developing a technique for measuring model error that filtered out the effects of chaos. When our group's results (which showed that most forecast error was a result of the model, with chaos a relatively minor effect) were accepted for publication and presented at conferences, there was initially no reaction from the meteorological community. But then the story was picked up by the media. Soon there were reports in newspapers and magazines and on radio shows in Europe, North America, and elsewhere. The reaction seemed out of proportion to the actual scientific interest; but everyone is interested in the weather, and everyone knows that the forecasts are wrong. The idea that the cause could be the models was apparently big news. Perhaps storms could be better predicted.

While this seemed a positive development, it didn't go down well. Criticizing models was apparently a good way to annoy the weather gods, or at least the weathermen.[12] Eventually, over a few years, the storm clouds dissipated. The work was published, and I moved on to different things. However, I remained struck by the deep blanket of denial that settled over those in the meteorological community, and by their emotional reaction to criticism, where any questioning of the model was interpreted as a personal attack. No matter the evidence to the contrary, they always believed that their models were right. It raised questions in my mind about the science and sociology of forecasting, questions this book attempts to answer.

I learned later that this lack of zeal in investigating model error was not unique. The work of Will Keepin and Brian Wynne at the International Institute for Applied Systems Analysis (IIASA) in Austria was proof of that. In 1981, the institute had just finished a multi-million-dollar project, involving over a hundred scientists, that was supposed to forecast the world's future energy consumption. After accounting for factors such as demographics and projected oil reserves, the computer model predicted that demand for energy would rise enormously over the next fifty years, and could be met only by building over a hundred nuclear power plants a year. Needless to say, this would have required a huge expansion in the nuclear industry, creating lucrative jobs for anyone with expertise in the energy field—such as, for example, the scientists who had built the model.

To Keepin, however, the model was so flexible, its connection to reality so tenuous, that "it was a bit like the Wizard of Oz. . . . Some guy was pulling on levers and making a big show, but it was a show determined by the little guy behind the curtain."[13] Almost alone in his criticism of the model, he decided to resign from his job. Just then, the British scientist Brian Wynne came to IIASA on a two-year contract to study the politics of science. He was looking for an insider to tell all about the energy model. After hearing Keepin's story, Wynne decided, to the institute's horror, to devote his two years to studying the other scientists' reaction to Keepin's critique. In 1984, the results were published in the top journal *Nature.*[14] The paper showed that the model had been biased in favour of nuclear and fossil-fuel energy producers, and that the model developers had tried to conceal its shortcomings.

Similarly, when the mathematician Benoit Mandelbrot questioned the assumptions behind modern finance, he found himself "about as welcome in the established church of economics as a heretical Arian at the Council of Nicene."[15] As the philosopher Thomas Kuhn pointed out, in science it is common, and even healthy, for new ideas to be met with skepticism by the establishment.[16] But if scientific models are used to set policy, and to make important public and private decisions, then we need to know how accurate they are. This is made difficult by the nature of the models, which are written in a highly specialized language that can be understood only by other scientists with experience in the field. Since such people often share the biases of the model makers, glaring problems go undetected, or unremarked.[17] Indeed, scientific institutions have become expert at deflecting serious public scrutiny of their work.[18] So to what extent can we trust their predictions for the future?

WHERE IS THIS GOING?

Forecasting has always attracted fraudsters and con men. When Kepler was trying to promote his predictive model of the sun, moon, and planets to Emperor Rudolph II, his competition was not so much other astronomers, but savants like the Englishman Edward Kelley, who preferred a talking mirror to calculations and was eventually jailed by the emperor for his poor performance. More recently, studies have shown that social forecasting, scientific and otherwise, is about as accurate as random guessing, despite the vast numbers of highly paid experts employed to do it.[19] If the futurologists of the 1960s had been right, for example, I would probably be writing this in an orbital space station as my personal robot tended to my toenails.

The accuracy of forecasts would not be so important if all that were at stake was the weekend weather or the likely return from government bonds in the next quarter. But like the residents of Caracas, we are becoming aware that the future need not resemble the recent past; the coming storms in weather, health, and wealth may be more intense than the kind we have grown used to.

It is only in the past few decades that human activities, like our use of large-scale industry and the automobile, have become comparable in scale to the workings of the planet itself. And it is even more recently that we have started to learn of holes in the ozone layer, the spread of chemical pollutants through the food chain, and the collapse of ocean fisheries because of overfishing. We have passed a kind of tipping point in our relationship with the world; our actions now influence its workings at every level. It used to be that the world happened to us; now we happen to the world as well. One day, as our children survey the damaged planet they have inherited, we may hear the question (asked less fairly of the Venezuelan president), Are you responsible?

The next fifty or one hundred years are going to be crucial, and we need to have a guide. In many ways, science got us into this fix, but will it help us to get out? And even if it can't tell us exactly where the world is headed, can it help us predict our own future health or play the stock market? To answer these questions, it is necessary to understand how scientists go about making forecasts. Equally important, though, is the history and sociology of science. Like any complex process, prediction is path-dependent: it matters how we got here.

My own short experience with the weathermen was, in the scale of things, a minor affair, a tempest in a teacup. I wasn't burned at the stake like Giordano Bruno, who had tried to convince the Inquisition that space was infinite, or threatened with torture and imprisonment for mocking the pope and arguing that the earth went around the sun, like Galileo Galilei. However, it did make me realize that in many ways, science has become rather like the Catholic Church of Galileo's time, and about as receptive to criticism. And just as we once looked to the Church to predict the future—just keep your head down until the Second Coming—we now look to the scientists for guidance.

We are all predictors, living by our forecasts. The most primitive bacteria have the ability to sense the presence of food and move towards it. Living beings are constantly interacting with their environment, reading and displaying information. Successful strategies—knowing when to hunt, when to run, when to sit it out—are coded in the genes. The practice of speed dating is based on the idea that first impressions count: within a few minutes of meeting a prospective mate, we somehow fast-forward through the whole relationship and predict whether it will work (and because this affects how much effort we put into the relationship, it can become a self-fulfilling prophecy).[20] We may not judge a book by its cover, but it certainly helps to scan the first few pages for a summary.

In science, though, forecasting plays a special role. Predicting the future is not a side activity of science, but has come to be seen as its primary pursuit.[21] A scientific theory is generally considered valid only if it can be used to predict the behaviour of a system. A theory that doesn't predict may be a beautiful or elegant idea, but it's no more functional, in the view of many scientists, than a piece of modern art. We may all be predictors, but for scientists, it's their profession. In this book, however, I will argue the following:

- **Mathematical models interpret the world in simple mechanical terms.** Scientific prediction, from ancient astronomy up to and including chaos theory, has been based on a highly abstracted, mechanistic view of the world, which is of limited applicability in the context of complex systems.
- **Living things have properties that elude prediction.** Systems where predictions are of interest—in biology, economics, or climate change—are either alive, influenced by life, or have a similar level of complexity to living beings. They are difficult to predict not because of simple technical reasons, which can be overcome with faster computers or better data, but because they have evolved to be that way. We pinpoint the causes of prediction error.
- **Forecasting has a large psychological component.** The desire to explain the world in terms of simple cause-and-effect relationships is a fundamental characteristic of human beings.

Predictions often tell us more about group psychology than they do about reality. Many prognosticators anticipated chaos in the financial markets in the new millennium, but the cause was supposed to be the Millennium Bug, not the collapse of Internet stocks. And accurate predictions, such as those that pointed out the vulnerability of New Orleans to a hurricane, are often ignored.[22]

- **Some predictions are still possible.** One type of prediction relates to overall function and can be used to make general warnings. The other type involves specific forecasts about the future. Mathematical models are better at the first than they are the second (Niels Bohr was right: predicting the future is hard).
- **We need to change our approach to prediction.** The current debate between climate modellers who argue that global warming is an imminent threat and skeptics who demand further proof can be resolved only with a fundamental shift in the kinds of predictions we make.

This book is divided into three main parts. The first is a brief history of the science of prediction. It will argue that modern forecasters are drawing on a long tradition of modelling the physical universe that stretches back to the ancient Greeks; and that throughout history forecasters have not just peered into the future but have helped shape the world we live in. Everything from our economic system to our relationship with nature and our own bodies has been profoundly affected by the early predictors, the model makers, the champions of cause and effect.

Of course, reading any such abbreviated history is a little like listening to a classic rock station on the radio. Just as each band is allowed to have only a handful of representative songs, so the great scientists have their life's work boiled down to a couple of greatest hits: Pythagoras and the Music of the Spheres, Kepler and his Harmony of the World, Galileo and his Stones. Minor scientists—the supporting acts—seem never to have existed, except as part of the occasional quirky sideshow. Unlike most classic rockers, though, the great scientists considered here are all European males. This is not because prediction is not practised by other races, or indeed by females, but because culture has played a role in the development of prediction as it is currently practised by scientists. And as the science historian Evelyn Fox Keller has pointed out, science has not been a gender-neutral pursuit.[23] These are subjects we will return to.

The second part of the book examines forecasting practice in the specific areas of weather, health, and wealth, and describes in detail the techniques currently employed by the scientists who make prediction their living. Like siblings, these three main areas of scientific prediction grew up together, share DNA, and show similar traits. To understand one, it helps to know the others. Finally, in the third part of the book, we see how these separate strands come together in a long-term forecast for the planet—culminating in a look at predictions for the year 2100.

The ultimate aim of the book is to make a forecast about forecasting, and to try to answer the question, Can scientists really look into the future? To find the answer, we must begin with the spiritual and intellectual forebears of modern numerical prediction—a secretive cult in ancient Greece led by a man they claimed was the son of Apollo.

PAST

1 ► SLINGS AND ARROWS

THE BEGINNINGS OF PREDICTION

All things are full of gods.
—Thales, Greek philosopher and mathematician

The truth of the model is not the truth of the phenomenon. It is a common confusion between these two kinds of truth—the norm in magic—that sometimes sanctifies the model (which is regarded as part of the real world) and gives the scientist the role of priest.
—Antoine Danchin, Pasteur Institute biologist

GAIA

According to Greek mythology, the first oracle, the maker of forecasts, was the earth goddess Gaia. She held forth at Delphi, which was named after the Greek word *delphus,* for "womb," and was literally the womb of the earth. Geographically, Delphi is located on a gentle slope on Mount Parnassus, about 150 kilometres northwest of Athens. On one side, the area is towered over by 300-metre cliffs that are known as the Phaedriades, or Shining Ones, because of the almost metallic way they catch the morning and evening light. The ground is nourished by the Castalian spring, which flows through a cleft in the cliffs. Below, a gorge filled with olive trees leads down to the Gulf of Corinth. The whole area is prone to storms, landslides, and other outbursts of the gods. It is watched over by birds of prey who ride the thermals of the cliffs.

The ancient Greeks believed this beautiful and dramatic place to be the centre of the universe. A legend states that the god Zeus released two eagles, one from the east, one from the west. When they met at Delphi, Zeus placed a stone, the *omphalos,* to mark the spot. Gaia's prophecies were sung out by a mythical figure referred to as Sybil, who inhaled trance-inducing vapours from a fissure in the mountain. The site was guarded by Gaia's daughter, the fearsome serpent Python, who lurked in the nearby Castalian spring.

Like his father Zeus, the god Apollo had an interesting and complicated life. He was god, among other things, of reason, music, plague, and archery. He had many love affairs, with both goddesses and mortal humans. But the young, inexperienced god's first big achievement—the one that put him on the map—was to slay the giant serpent Python:

> E're now the God his arrows had not try'd
> But on the trembling deer, or mountain goat;
> At this new quarry he prepares to shoot.
> Though ev'ry shaft took place, he spent the store
> Of his full quiver, and 'twas long before
> Th' expiring serpent wallow'd in his gore.[1]

Since Python was Gaia's daughter, amends had to be made for this violent deed. Apollo worked for eight years as a cowherd to purify himself. But once that was done, he returned to Delphi and, in a hostile takeover, claimed the oracle from Gaia. From that moment on, he was known as Pythian Apollo, the god of prophecy, and Delphi was his main shrine.[2]

That's the mythology. Archaeological excavations have shown that from 1500 to 1100 B.C., the site was occupied by small Bronze Age Mycenean settlements that were dedicated to the Mother Earth deity. The new god Apollo arrived, perhaps via invading Dorians, and began to dominate. So in both versions, a power shift takes place between Gaia and Apollo. The chaos theorist Ralph Abraham refers to this time in human history as a major bifurcation point, where "the goddess submerged into the collective unconscious, while her statues underwent gender-change operations."[3] The result was the most successful prediction business in history. For almost a thousand years, the Delphic Oracle called the shots in business, politics, religion, and war.

The biographer Plutarch, best known for his lives of famous Greeks and Romans, served as a priest at Delphi, and from his histories we have some knowledge of the inner workings of the Delphic sanctuary.[4] The oracle, known as the Pythia, was always a woman, since women were thought to be more receptive to Apollo's oracular powers. Like a telegenic TV presenter, the Pythia didn't make the forecasts herself, but only channelled the predictive power of Apollo. The main job requirements were *enthousiasmos* (which in its original sense meant not enthusiasm but "possessed by a god") and faithfulness to Apollo. She was not allowed to have intimate relations with anyone, even a husband, for Apollo was a jealous god. A case in point was Cassandra. Apollo attempted to seduce her by granting her prophetic powers, but she refused him. In revenge, he cursed her so that no one would pay attention to her predictions.

The oracular ceremonies were held once per month, except during the three-month winter break, when Delphi was often covered in snow. Suppose you are a *theoprope,* a supplicant. You arrive by boat at the harbour of Kirrha, in the Gulf of Corinth, then make the journey up into the mountains, reaching Delphi as night falls.

You have with you two things: a written question and, for reasons that will become obvious, a young goat (which you purchased from a goatherd outside the town). You spend the night at a crowded inn, then get up early the next morning to join the long line of people outside the temple. In your mind is the question you have carried all this way. Perhaps it relates to a marriage, or treatment of an illness, or a business concern.

Your growing anxiety isn't helped when you notice that some people appear to be jumping the queue, after offering the priests extravagant bribes. But finally it is your turn. A priest beckons you to climb the steps of the temple. In your arms is the small, warm goat. You feel it trembling with fear. You hand it to the priest, who takes it towards a blood-stained altar. Another priest has at the ready a long bronze blade. On the walls, you notice, are inscribed rather bland motivational messages. Know thyself. Avoid excess. A single letter *E.* What can that mean? While the first two priests busy themselves with the poor struggling animal, another leads you to the spring near the temple. You have to shower before they will let you into the pool. As you wash, you try to close your ears to the goat's plaintive bleats, which are soon followed by silence. You hope that Apollo is satisfied by the humble sacrifice.

Once purified, you are led by a high priest to the inner sanctum. And there she is: the Pythia, the oracle. She sits on a three-legged bronze stool, the tripod. The room, you notice, has a peculiar sweetish smell—some strange vapour that seems to be emanating from the earth itself.[5] The Pythia is a middle-aged woman. Her hair is thin and grey, her eyes appear glazed. She doesn't seem to notice you come in. Suddenly, you feel very afraid of this person.

Before you can back out of the room, the high priest reads your question aloud. Again, the Pythia fails to react. She sways slowly back and forth on her tripod. You wonder if she has heard.

But then she starts to make a noise. Not exactly speech or singing, but something in between, on the edge of sense and nonsense. You listen, but it is like trying to make sense of the call of birds or the rustling of leaves in a storm.

After some time, you're not sure how long, the Pythia falls silent. It is as if a switch in her head just turned off. You notice how drained she looks. The high priest steps forward. Whatever language she was speaking, he must understand it, because he reads out a neat response in hexameter verse. You're trying to figure out what it means as they lead you down the steps of the temple. And you're still trying to figure it out days later, when you eventually get home. But when you announce your decision to your waiting family, it feels like you knew it all along.

According to the philosopher Heraclitus, the Pythia never gave a straight answer, but only hinted at the truth. King Croesus of Lydia famously asked the Pythia if he should invade Persian territory. The oracle told him that if he did, a mighty empire would be destroyed. He took this as a green light, but unfortunately, the empire she was referring to was his own.[6]

Despite the equivocal nature of the prophecies, the oracle played an enormously important role in Greek culture, especially in the Archaic period (the eighth to sixth centuries B.C.). Most major decisions about war or politics were made in consultation with it. The oracle retained its power for almost a thousand years, gradually falling into decline with the rise of Christianity, and in the third century A.D., it made its final prediction: the gods would no longer speak at Delphi.

APOLLO'S ARROW

The poet Iamblichus relates a tale about the oracle when it was still at the height of its powers. A gem engraver called Mnesarchus visits to ask whether a journey he is about to undertake will be profitable. The oracle replies that it will; furthermore, the man is told, his wife, who unknown to him is pregnant at the time, will give birth to a son "surpassing in beauty and wisdom all that had ever lived."[7] Mnesarchus realizes that the child has been sent by the gods. When he is born, he is named Pythagoras, "signifying that such an offspring had been predicted by the Pythian Apollo."[8]

Mathematician, philosopher, even Olympic trainer, Pythagoras would go on to found a new system of prediction based not on oracles but on the power of numbers. He was literally a demigod to the Greeks—some said he had been fathered by Apollo.[9] This was a story that his many followers never denied. A proof of Pythagoras's divinity was thought to be his golden thigh, a description that perhaps referred to a birthmark. Iamblichus tells of Abaris, a Hyperborean priest or druid, who was returning to his home in the north after a fundraising mission for his temple. The Hyperboreans were the ancestors of Celtic tribes and worshippers of Apollo. On his way through Italy, Abaris saw Pythagoras and became convinced by his appearance that he was none other than Apollo himself. He offered Pythagoras the most precious thing in his possession, a sacred arrow said to have belonged to Apollo, like the ones that killed Python. The arrow, Abaris claimed, had magical powers: whenever he had encountered obstacles on his travels, such as impassable rivers or mountains, the arrow had enabled him to fly across. He had used it also to stop epidemics and to purify Sparta of a mysterious toxin that was poisoning the city (perhaps toxic gases rising from Mount Taygetus).

Pythagoras accepted this magical arrow without any hint of surprise, "as if he was in reality a God himself."[10] He took Abaris aside, showed him his golden thigh to prove that Abaris was not mistaken, and explained that "he had come for the purpose of remedying and benefiting the condition of mankind, and that on this account he had assumed a human form, lest men being disturbed by the novelty of his transcendency, should avoid the discipline which he possessed."[11]

No written works by Pythagoras have survived. We know that he was born on the island of Samos, in the Aegean Sea, sometime in the sixth century B.C. In his life, he travelled and studied extensively: with the mathematician Thales of Ionia (who forecast the yields of harvests, and predicted an eclipse of the sun in 585 B.C.), the Phoenician sages of Syria, and the high priests of Egypt. He stayed in Egypt until the Persians invaded and he was taken to Babylon. He spent a further several years in the capital of Mesopotamia before finally returning to Samos.

In Samos he set up a school, known as the semicircle, to study philosophy and hold political meetings. He lived outside the city in a secluded cave, where he carried out his mathematical research. As his popularity and reputation grew, the citizens of Samos began to draw on his help with city affairs, intruding on the privacy and calm that he required for his studies. At about the age of forty, Pythagoras left Samos and went to Croton, in southern Italy. There he formed a new, secretive society.

THE MOST PERFECT NUMBER

As both teacher and spiritual leader, Pythagoras attracted hundreds of students. Those in his inner circle, both men and women, were known as *mathematikoi*. To join the commune, they had to give up all personal possessions, follow a strict vegetarian diet and ascetic lifestyle, and study five years under a vow of silence. Pythagoras explained that the aim of these privations was to train the applicant's power of reason: "Excess brings lust, intoxication and uncontrolled emotions, which drive men and women into the abyss. Greed brings envy, theft and exploitation. These thickets, which choke the soul, must be cleared out by systematic discipline, as if with fire and sword. Only when reason is liberated from such evils are we able to implant what is useful and good within the soul."[12]

The *mathematikoi* were the hard-core Pythagoreans, the true priests of Apollo. They could quit the arduous program whenever they wanted, and recover all the material goods they had donated, times two. But if they did, a monument was constructed to them as for a burial, and they were regarded as dead; every time a Pythagorean passed them in the street, he would act as if they had never met.

The outer circle were known as *akousmatics.* They lived in their own houses, kept their possessions, were allowed to eat meat, and visited the society only during the day. However, they were not allowed to see Pythagoras, and were not taught the cult's inner secrets. When the *akousmatics* attended lectures, they sat in the back, separated from the master by a screen. They were never shown mathematical proofs, and instead had to accept the results *ipse dixit,* because Pythagoras said they were so.

Life in the commune adhered to a strict routine. Solitary or group walks were followed by lectures on astronomy, music, or mathematics; corrective counselling; and exercise sessions similar perhaps to Tai Chi or yoga. Some of the exercises might have been of Pythagoras's own devising; while in Samos, he had turned the athlete Eurymenes into an Olympic champion by making him follow an arduous training regimen. Lunch was bread and honey or honeycomb; dinner was vegetarian. In the evenings, Pythagoras would give lectures. These were typically attended by at least 600 people, with the *mathematikoi* at front and everyone else shielded by the screen.

One of the topics for the evening lectures was no doubt foretelling the future. Pythagoras had studied under Thales and was said to have surpassed his mentor in the art of prognostication. Like Thales, he is said to have been able to predict eclipses, harvests, and earthquakes, and perhaps through his influence with Apollo, could halt epidemics and calm storms. He taught many systems of prediction, such as the reading of entrails or listening to oracles. But for him, the highest form of prediction was divination through numbers, which Pythagoras thought connected more closely with the "celestial numbers of the gods" than other methods.[13] One of his students, Empedocles, became known as Alexanamos, or "Averter of Winds," for being able to predict and control the weather. (His modern counterpart is the U.S. evangelist Pat Robertson, who claims to have used the power of prayer to steer the course of hurricanes.) Just as Apollo's arrow had enabled Arabis to dart across landscapes without needing to traverse mountains or rivers, so the magic of numbers allowed the Pythagoreans to dart through time and foresee future events without having to wait for them to happen.

The details of how this system of numerical prediction worked remain unknown, since the group was obsessed with secrecy. According to Iamblichus, "Their writings and all the books which they published were not composed in a popular and vulgar diction, so as to be immediately understood, but in such a way as to conceal, after an arcane mode, divine mysteries from the uninitiated."[14] Rather than rely on written records, the Pythagoreans were trained to improve their powers of memory; each morning before arising, for example, they would recount to themselves the exact events of the previous day. We would know little of Pythagoras's teachings if it weren't for the writings of subsequent philosophers, such as Plato and Aristotle. This secrecy certainly also added to Pythagoras's mystique.

For the Pythagoreans, numbers were much more than a tool for prognostication. Rather, they were what united the reason of man with the workings of nature. Each number was a kind of mystical entity with its own special properties. By understanding these properties, man could gain insight into the workings of the world, see into the future, and become closer to the gods.

The monad represented the initial unified state from which the universe was created, and was associated with divine intelligence. The division of the monad into the dyad, the number two, symbolized polarization: unity became duality. The dyad therefore signified mutability, or the ability to change appearances, and also unlimited excess, conflict, and indeterminacy—all negative qualities in a commune where applicants were selected for their ability to control anger and passion. "Lamentations, weepings, supplications, entreaties were considered abject and effeminate and neither gain, desire, anger, ambition nor anything of a similar nature became the cause of dissension among them."[15] The number three, the triad, enabled all things with a beginning, a middle, and an end, or a past, a present, and a future. It was the number associated with prophecy, as in the tripod at Delphi. Number four, the tetrad, represented completion, as in the four seasons that make up a year. The greatest and most perfect of all numbers was the decad, ten. Just as the first four numbers sum to ten, the decad was also the sum of the laws of nature. The following arrowhead arrangement of ten dots, known as the *tetractys,* was used by the Pythagoreans as a sacred symbol:

RIGHT VS LEFT

The dyad represented the division of the universe into two groups. Table 1.1, a list of ten pairs of antitheses, was compiled by the Pythagoreans in reference to the decad and documented in Aristotle's *Metaphysics*. These antitheses were believed to represent fundamental organizing principles of the universe.

TABLE 1.1

Limited	Unlimited
Odd	Even
One	Plurality
Right	Left
Male	Female
At Rest	In Motion
Straight	Crooked
Light	Darkness
Square	Oblong
Good	Evil

Pythagoras believed in reincarnation and claimed to be able to remember his past lives. He once rescued a dog from being beaten on the street and told the owner that he could tell by the animal's cries that it was the soul of his late friend Abides. Through repeated incarnations, the Pythagoreans believed that they could choose limited over unlimited, light over darkness—the first column over the second—and thus achieve divinity.[16]

Why the Pythagoreans chose these particular items for their list of opposites is unclear (though we explore some possible reasons later). It is interesting to compare it with the following lists (on page 30), which are from very different sources.

TABLE 1.2

Left Brain/Right Side	Right Brain/Left Side
Intellect	Intuition
Abstract	Concrete
Analytic	Holistic
Rational	Intuitive
Objective	Subjective

TABLE 1.3

Yang	Yin
Odd	Even
Conscious	Unconscious
Right Side	Left Side
Masculine	Feminine
Aggressive	Yielding
Light	Darkness
Reason	Emotion

TABLE 1.4

Physical Science	The Humanities
Hard	Soft
Determinism	Free Will
Reason	Feeling, Emotion
Objective	Subjective
Quantity	Quality
Specialism	Holism
Prose	Poetry
Male	Female
Clarity	Mystery

The list in table 1.2 was the result of so-called split brain studies, conducted with patients who had been disabled by extremely severe epileptic seizures.[17] The human brain is divided into two hemispheres, with the left controlling the right side of the body and vice versa. In a last attempt at therapy, connections between the two hemispheres were severed to stop the seizures spreading across the brain. While the treatment succeeded in controlling the seizures, it effectively isolated the two sides. Through a series of experiments, the researchers attempted to determine the functions of each hemisphere. The left brain, they came to believe, is associated with abstract, rational thinking, and the right brain with holistic and intuitive modes of thought. In a healthy brain, the two sides work in concert, so it is never possible to cleanly separate their functions.

Table 1.3 is from the I Ching, or Book of Changes.[18] From these tables, one might deduce that Pythagoras was a left-brain (right-hand) kind of guy, more yang than yin. As Iamblichus wrote, "The right hand he called the principle of the odd number and is divine, but the left hand is the symbol of the even number and of that which is dissolved."[19] Apollo was the god of reason, and one of the commune's aims was to elevate rational, objective reasoning over subjective, emotional behaviour. (The preference for the right hand has continued in our language—the word "sinister" is from the Latin for left.) Table 1.4 is from a longer list compiled by the philosopher Mary Midgley, who wrote in 1985 that the instruction to keep with the items in the first column "has for the last century usually been issued to English-speaking scientists with their first test-tube and has often gone with them to the grave."[20]

Science has changed a great deal since the time of Pythagoras, but the emphasis on using reason and analysis to provide hard, fixed solutions for particular, specialized problems has remained the same. The development of quantum physics, which revealed the wavelike properties of matter, along with attempts to adopt a rounder, more holistic perspective, as in systems biology, has softened this distinction. But scientists on the whole are still squares, not oblongs, and the idea, so prevalent in science, that complex phenomena should be reduced to simple ones is Pythagorean. As we will see, this tendency to drive on the right has been both the strength and the weakness of scientific forecasting.

MUSIC OF THE SPHERES

Like Apollo, who was frequently portrayed with a lyre, Pythagoras was a musician. He believed that music had healing powers and could be used to calm the soul. A powerful proof of the importance of numbers was the discovery, attributed to him, of their role in music. A string on a lyre, when plucked, will give a particular note. Fretting the string at a position halfway down gives a note differing by an octave; a third of the length down gives a musical fifth; and one quarter the length a musical fourth. Use a different string, or an electric guitar, and the same relationship holds.

Pythagoras realized that the relationship between pleasing notes was all a question of numbers. And if music, one of the most expressive art forms, could be reduced to numbers, then so perhaps could everything else. In the Pythagorean cosmos (a word he invented), the stars, planets, moon, and sun were contained in nested, concentric, transparent spheres, all of which rotated around the earth according to a cosmic harmony, which Pythagoras called the Music of the Spheres. He argued correctly that the earth itself was a sphere that caused night and day by its revolution, and that the seasons were the result of the angle of the earth's axis with the sun. Even time itself was cyclical, repeating itself once every Great Year. This was the period it took the sun, moon, and planets to return to the same configuration, estimated by ancient astronomers to be around 10,800 years.[21]

Pythagoras is credited with a number of mathematical discoveries, including the properties of what are now called the Platonic solids—the pyramid-shaped tetrahedron, cube, octahedron, dodecahedron, and icosahedron. (Every face of these polyhedron figures is identical, and remarkably only five exist.) However, he is best known for his famous theorem, which states that in a right triangle, the square of the side opposite the right angle equals the sum of squares of the other two sides. While the Egyptians and Babylonians were probably aware of this relationship well before Pythagoras, at least for certain triplets, the Pythagoreans appear to have been the first to generalize the concept. Just as the theory of musical harmony applies to any instrument, the Pythagorean theorem applies to any right triangle. As the Pythagoreans understood, the power of mathematics comes from knowing that a single law holds in all cases—from reducing the plurality to one. The theorem is still one of the most important results in mathematics, and it's used in everything from engineering to nuclear physics.

FIGURE 1.2. The theorem of Pythagoras: $A^2 + B^2 = C^2$.

The Pythagoreans believed, almost as an article of religious faith, that the world was made up of positive integers and their ratios, such as the fraction ¾, which are called rational numbers. Ironically, Pythagoras's theorem about triangles led to the discovery of numbers that cannot be expressed as a ratio. A right triangle with two sides both equal to one unit has a hypotenuse (from the theorem) of the square root of two. Hippasus, one of the Pythagoreans, showed that the root could not be expressed as a ratio of two integers. In other words, it was irrational. His comrades could not accept that such a number existed: it was as if someone had found a bum note in the music of the spheres. Hippasus made the mistake of publicizing the results openly, "to the profane and to those . . . without disciplines and theories."[22] He died shortly afterwards under mysterious circumstances. It was said that "the Divine Powers were so indignant that he perished in the sea."[23] (See notes for a proof that Hippasus was right.[24])

It is strange that numbers that cannot be expressed as a ratio of whole numbers are called irrational, as if they were in some way deviant; there are far more of them than there are rational numbers, just as there are many more pitches of sound than those found on a keyboard. In fact, if you could choose only one number by throwing an imaginary dart at the interval from zero to one, the chances of hitting a rational number are zero.[25] You might aim to hit ½, but you'd actually get some irrational number with an endless sequence of digits, like 0.5083428 . . .

The Pythagorean commune grew in both size and power, to the point where it exerted considerable influence over Croton and the surrounding area. It is even believed that Pythagoras became the local "master of the mint," bringing the first metal coinage to the region.[26] Eventually, though, this rational society became the victim of seemingly irrational forces. People—especially those who had been excluded from membership—began to speak against the secretive and elitist group. The citizens started to harass the Pythagoreans in the streets. When a number of them assembled at the house of Milon, an Olympic athlete, a mob surrounded them and set the house on fire; only two escaped the conflagration. In another incident, forty members of the group were attacked and killed. Pythagoras himself managed to escape, and probably died in exile. Even Apollo's arrow was no protection against the madness of crowds; but the demise of the Pythagoreans marked only the first stage in the development of numerical prediction. As the novelist and philosopher Arthur Koestler wrote of Pythagoras: "His influence on the ideas, and thereby on the destiny, of the human race was probably greater than that of any single man before or after him."[27] He didn't just predict the future; he also helped define it.

THE ACADEMICS

Since the Pythagoreans didn't believe in recording their methods, our accounts come mostly from future documenters. One of these was a man born, it is said, with the name Aristocles. His mother and father came from famous, wealthy families in Athens. His uncle was a friend of the philosopher Socrates. Perhaps because of his physical bulk—he was a trained wrestler—or the width of his forehead, he was usually known by his nickname, which roughly translates to "the broad." He was Plato.

Like Pythagoras, Plato was a man of many talents. He knew the arts of politics, philosophy, and war. He was also a playwright. According to Diogenes, he began his career as a writer of tragedies. After hearing Socrates talk, however, he gave up on the theatre, and even set fire to a play that he had been planning to enter into a drama competition. Instead, he began pouring his creative energy into the writing of philosophical dialogues. While these weren't plays, they did show his enormous skill at crafting entertaining dialogue. They also often blur the line between fiction and nonfiction. It is hard to know whether the dialogues represent things that were actually said or are a fictionalized account. Or whether they even represent what Plato himself thought on a subject.

An example of this ambiguity is to be found in Plato's *Defence of Socrates.* Socrates, the son of a sculptor, was another servant of Apollo who dedicated his life to understanding the causes that underlie the universe. This quest took on a new form after his friend Chaerephon visited the Delphic Oracle and asked whether there was anyone who was wiser than Socrates. The Pythia replied that there was not. Since Socrates was unaware of any wisdom within himself—he often joked that "the only thing I know is that I know nothing"—he interpreted this to be a mission from Apollo to visit those who claim to be wise and discover their wisdom. He therefore went to poets, artisans, and statesmen across the land, but after closely questioning them, he realized that they were not wise at all. "And so I go my way, obedient to the god, and make inquisition into the wisdom of anyone, whether citizen or stranger, who appears to be wise; and if he is not wise, then in vindication of the oracle I show him that he is not wise; and this occupation quite absorbs me, and I have no time to give either to any public matter of interest or to any concern of my own, but I am in utter poverty by reason of my devotion to the god."[28]

Needless to say, this attitude annoyed a lot of people. In 423 B.C., Aristophanes wrote a comedy called *The Clouds,* in which the main character, also called Socrates, worships clouds and other natural phenomena rather than the gods. The play was produced in a competition at the Great Dionysia. It came third out of three plays but was published a few years later. The Greeks were avid theatre-goers, and the play turned Socrates into first a figure of fun, then a tragic anti-hero.

Twenty-four years after *The Clouds* was produced, Socrates found himself on trial, accused of believing in new divinities and corrupting the youth. Perhaps his accusers were confusing the character in the play with the real person. Plato's *Defence of Socrates* is a dramatic account of how the philosopher defended himself against the citizens of Athens. It is not known whether it is a verbatim transcript of what Socrates said, a heavily edited version, or a fictionalization that is really Plato's defence of his friend and mentor. Again, the story and the reality are hard to separate.

In any case, according to Plato, the jury was not convinced by Socrates' case. The prosecutors were seeking the death penalty, but Socrates was given the chance to offer an alternative. He first suggested free meals for himself for life. This didn't go down well, so he suggested a nominal fine of one mina. As Socrates dug a deeper and deeper hole for himself, his friends, including Plato, offered to pay a more substantial fine. But it was to no avail, and Socrates was put to death by poisoning with hemlock.

The death of Socrates was not in vain, for it had a huge impact on Plato. Sick of the politics of Athens, he travelled to Egypt, Sicily, and Italy. It was in Italy that he learned of the work of Pythagoras and met his disciples. From them, according to the scholar G.C. Field, he formed the idea "that the reality which scientific thought is seeking must be expressible in mathematical terms, mathematics being the most precise and definite kind of thinking of which we are capable."[29] The only way to overcome the ignorance that Socrates had exposed was with numbers.

When Plato returned to Athens, around 387 B.C., he established what became the longest-running learning institution in the history of mankind—the precursor to today's universities. The Academy, so named because the land belonged to a man called Academos, was dedicated to research and instruction in philosophy and science. Over the door was written, "Let no one unversed in geometry enter here." Plato's concentration on precise definitions, clear statement of hypotheses, and rigorous proofs of mathematical conjectures all prepared the ground for the major mathematical developments of ancient Greece, which underpin modern science. The Academy survived more than 900 years, until the Christian emperor Justinian, claiming it was a pagan establishment, closed it down in 529 A.D.

Students at the Academy would spend ten years studying the sciences of astronomy and mathematics, then five years studying dialectic (the art of posing and answering questions). Plato believed that dialectic was the path to wisdom, and through his dialogues, he contributed to the theory of arts from poetry to epistemology. He taught that material objects were imperfect versions of underlying forms, which existed in a static way, independent of time and space. An example of a perfect form was a mathematical object such as a line. A material manifestation of a line, such as a line drawn in the sand, was only a flawed reproduction of the real thing, like a poor photocopy. Every object had an associated form, which it yearned to be but could never reach. The plurality of different tables, for example, all aspired to the one true table. To Plato, the ultimate reality was not the chaotic, imperfect world that we see and hear and taste, but rather the abstract, eternal world of pure forms. Our world was just a blurred shadow of the real thing.

MATHEMATICAL BIOLOGY

In 430 B.C., the citizens of Athens were struggling with the real-world problem of infectious disease. Thucydides gave a graphic description of the plague that was afflicting the city. People were first attacked by "violent heats in the head, and redness and inflammation in the eyes,"[30] along with sneezing, hoarseness, and a cough.

"Discharges of bile of every kind named by physicians ensued, accompanied by very great distress." The skin was "reddish, livid, and breaking out into small pustules and ulcers. But internally it burned so that the patient could not bear to have on him clothing or linen even of the very lightest description; or indeed to be otherwise than stark naked. What they would have liked best would have been to throw themselves into cold water; as indeed was done by some of the neglected sick, who plunged into the rain-tanks in their agonies of unquenchable thirst; though it made no difference whether they drank little or much." In most cases, the disease proved fatal after seven or eight days. Some, like Thucydides himself, survived but were often maimed or blinded.

Near the height of the plague, a delegation was sent to Delphi to ask the oracle how it could be stopped. The oracle's reply was that the altar of Apollo on the island of Delos, which was in the form of a perfect cube, should be doubled in size. In response, the delegates arranged for each edge of the cube to be extended by a factor of two; however, this increased the volume not by two but by eight. The oracle announced that Apollo—whose arrows were believed to cause plague sores—had been angered by this sloppy arithmetic, and indeed the outbreak grew worse.[31] Plato was consulted. He told them, "The god has given this oracle, not because he wanted an altar of double the size, but because he wished in setting this task before them, to reproach the Greeks for their neglect of mathematics and their contempt of geometry." Only the magic of number could defeat the plague.

Perhaps he was right, because soon the plague began to ease, though not before claiming about a third of the population of Athens. The problem of how to double the cube didn't go away, though. The Athenian mathematicians, at least those still surviving, believed that all mathematical problems could and should be solved using only a compass and a ruler, tools that corresponded to the perfect forms of circles and straight lines. Anything that couldn't be expressed in these terms was out of bounds. Just as the Pythagoreans eventually encountered a problem that could not be solved by rational numbers, however, the Athenians found that many of their problems could not be solved with these two tools alone. They could not construct a square with the same area of a given circle or double a cube or trisect an angle into three equal angles. Their insistence on static forms stood solidly in the way of progress.

Eventually, solutions for all these challenges were arrived at using so-called mechanical curves. These needed to be traced out by sliding lines around a point. Because they introduced the idea of change and motion—a bad thing in Pythagoras's list—they were not considered to be real geometry.

THE GREEK CIRCLE MODEL

To Plato and other philosophers of his time, the universe was not a place of chaotic flux and change but a kind of endlessly repeating cycle. Like Pythagoras, Plato thought that time moves in circles. The future had already been determined, and it was the past. Because events did not occur randomly, but were known in advance, it followed that the future could be predicted. The logical place to start was up above, in the heavens.

The exemplars of circular, repetitive motion were the stars and the planets, which were believed to move in perfect circles around the earth. Indeed, careful observations of the stars showed that they did move in a circular fashion. The planets—in particular Mars, Jupiter, and Saturn—were more tricky. Their path around the night sky involved a fair amount of wandering (the word "planet" is from the Greek for wanderer) and even backtracking. It seemed they had a life of their own. For example, Mars advanced around the sky from west to east, completing a revolution in about 780 days; but partway around it would stop, backtrack a little, and then resume its forward motion. And 780 days later, it would do the same thing.

The wanderings of the planets seemed incompatible with simple circular motion, but Plato's associate Eudoxus managed to come up with a model for the universe that captured such effects.[32] Imagine the earth surrounded by a huge crystalline sphere that contains the stars. The sphere rotates around us once per day. Inside this sphere is a separate transparent sphere that contains the sun. It too rotates around the earth once a day, but it also rotates annually at an approximate 23.5-degree angle to the line joining the centre of the earth to the North Pole. The angle accounts for the seasons, since half the year one side of the globe will receive more sun, while the other half of the year it receives less (as shown in figure 1.3 on page 42). This much was simple; the movements of the planets were more complicated. These were also modelled by spheres, whose axes of rotation were fixed to other spheres (which could themselves rotate). The resulting nest of twenty-seven rolling spheres was capable of producing highly complex motion. With carefully selected rates and angles of rotation, the model could adequately represent the motion of the heavens.

This model, which I will refer to as the first Greek Circle Model, was an amazingly ingenious geometrical accomplishment, and it can be viewed as a direct precursor to the mathematical models that are used today to simulate physical systems. Of course, it was purely descriptive, and was based on a hypothesis of circular motion, as opposed to rigorously derived physical laws of motion. The fact that it worked quite well as a model of the universe is a poignant reminder that a model that can be made to fit the data isn't necessarily an accurate representation of reality.

North Pole

Sun

South Pole

FIGURE 1.3. The angle of the earth relative to the sun means that each hemisphere gets more sun in half of the year (its summer) and less in the other (winter). The angle actually varies from 21.8 to 24.4 degrees, returning to centre about every 42,000 years, owing to slight wobbles in the planetary system.

THE WORLD'S TUTOR

The Academy was the elite institution, the Ivy League or Oxbridge of its time, and many of Plato's students went on to make major contributions to Greek science and philosophy. His star student was Aristotle, who stayed at the Academy for twenty years, from the time he was eighteen until Plato's death in 384 B.C. Aristotle then took a job with King Philip of Macedonia, tutoring his son Alexander for three years. We are familiar with the work of Aristotle and Plato largely because of Alexander the Great. When Alexander went to Delphi to obtain his oracle, the Pythia refused. He kept insisting, and even threatened her with force. Finally, she told him, "You can do what you like."[33] This was like telling George W. Bush not to hold back so much, and Alexander went on to conquer the Middle East, Persia, and Egypt, as well as parts of Afghanistan, Central Asia, and India. The library in one of the cities named after him—Alexandria, in Egypt—became the major repository of

Greek knowledge, and eventually cemented Aristotle's position as tutor to much of the world.

In 355 B.C., Aristotle returned to Athens and set up his own institute, called the Lyceum after the old temple of Apollo in which it was located. Like the Academy, the Lyceum taught a range of subjects, such as politics, ethics, and science. While Plato was fascinated by the abstract properties of forms, Aristotle's science was more grounded in observation of physical and natural phenomena. For example, he collated descriptions of about 500 different types of animals, many of which he dissected. In Raphael's painting *The School of Athens,* Plato is shown gesturing to the heavens while Aristotle is lowering his hand to the ground, as if to bring the theorist back to earth.

Aristotle viewed material substance as bestowed with a kind of life force with its own wants and desires. He believed that all substances were composed of the four elements—earth, water, air, and fire. The tendency of earth is to sink strongly down. Water trickles down less strongly, while air rises and fire positively springs to the sky. An air bubble in water will rise upwards because air "wants" to be higher than water. Motion, therefore, occurs either because an object wants to find its own level or because it is pushed. A full explanation of any object had to take into account its final cause, the purpose for which the thing existed. The stars in heaven were made of the fifth element, called ether, the lightest of all, and moved in a circle, which was the figure of eternal motion. Earth had to be in the middle of the universe, because it was the heaviest thing around.

In this teleological view of the world, the earth itself was a kind of organism. Natural phenomena such as earthquakes, winds, or even meteors were the result of the planet's "windy exhalations." The son of a doctor, Aristotle constantly drew comparisons between the earth and human bodies. He believed that tremors or spasms were caused by a kind of wind within the body, and that earthquakes were caused by a similar wind, but on a larger scale.

Perhaps Aristotle's most significant contribution to science was his axiomatic development of logic. In his work *Prior Analytics,* he proposed his syllogistic form of argument—the ultimate in linear, left-brain thinking—which consisted of two premises and a conclusion. His gloomy but hard-to-counter example was:

(i) Every Greek is a person.
(ii) Every person is mortal.
(iii) Every Greek is mortal.

(One imagines that the first spinoff from the Lyceum was a life-insurance company.) This systematic, logic-based approach to science laid the foundation for Euclid's development of geometry and helped establish what became known as the scientific method.

While Aristotle's work in biology has been much admired, his theories in physics were less reliable. He postulated two laws of motion. The first was that the heavier an object is, the faster it will fall. The second was that the speed of fall decreases with the density of the medium—so, for example, a stone will fall more slowly in water than it will in air. Curiously, while Aristotle made detailed observations of many biological specimens and natural phenomena, he didn't verify his theories of physics. It was left to Galileo, nineteen centuries later, to actually drop stones off buildings and disprove Aristotle's first law.

GREEK CIRCLE MODEL, VERSION II

At the Lyceum and elsewhere, astronomers continued to improve the Greek Circle Model. The original version of Eudoxus captured both the daily and yearly cycles of the sun and the general motion of the planets, but it didn't match some of the details. In particular, it was known that the seasonal motion of the sun, as measured by the time between solstices, was not uniform. This was repaired by adding more spheres of motion. The final model, which was presented by Aristotle and accounted for the motions of all the visible planets and the moon, included no fewer than fifty-five concentric spheres. It matched the observed movement of the planets around the sky and consisted solely of circular motion, which was the only type that could occur in the ether.

After Aristotle's death, a mathematician called Aristarchus of Samos proposed the novel theory that the earth revolved around the sun, rather than the other way round. The stars do not rotate around the earth, he suggested, but stay in their positions an enormously far distance away. (The large distance was required so that the stars appear not to move relative to one another as the earth rotates.) Perhaps because it was incompatible with the views of Aristotle, the idea did not catch on.

The serious mathematicians continued to tinker with the Greek Circle Model. Around 150 A.D., Ptolemy of Alexandria put the finishing touches on a new version. It included some tweaks of Aristotle's model, and some major changes. It was known that the size of the moon and the brightness of the planets tended to vary, which suggested that their distance from the earth changed with time. The most straightforward way to address this would have been to adopt non-circular motion, but again this would have contravened dogma. Ptolemy wrote: "Our problem is to demonstrate, in the case of the five planets as in the case of the sun and moon, all their apparent irregularities are produced by means of regular and circular motions (for these are strangers to disparities and disorders)."[34] He achieved this by incorporating a new type of circular motion, first proposed by Hipparchus, known as epicycles—that is, circles within circles. In Ptolemy's model, the planet rotates around a small circle, which in turn rotates around the earth (as shown in figure 1.4). Its distance from the earth therefore varies, as does the rate at which the planet moves. Working all this out required the invention of trigonometry, which some attribute to Hipparchus.

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FIGURE 1.4. In the Greek Circle Model, Version II, planets move in epicycles—circles within circles.

With its cycles, epicycles, and even eccentric epicycles (whose centres were slightly offset from the main cycles), the entire model was even more complicated than Aristotle's. By insisting at a basic level on the Pythagorean simplicity of circular motion, the model effectively exported the system's complexity to a higher level. The extreme flexibility in the model meant that it could be made to closely match the observational data. Ptolemy wrote up his results, which included scores of tables detailing the motions of the heavens,