NO MORE MEASLES!

The Truth About Vaccines and Your Health
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Like many Americans, I was brought up to believe that democracy is a good thing and that free and open debates are essential to democracy. Unfortunately, something seems to be going wrong with the way we in the United States engage in debates. Our debates seem to be generating more heat than light. Our debates about vaccination have been particularly ugly. Vaccine researchers have received verbal abuse and even death threats. Can you imagine the other castaways on *Gilligan’s Island* treating the Professor that way?

The word *science* comes from the Latin word for knowledge, but it refers to knowledge of a particular kind. *Science* refers to knowledge that is gained through a logical analysis of careful observations, including the results of experiments. *Science* can also refer to that process for gaining knowledge. A scientist is someone who dedicates his or her life’s work to gaining knowledge in that way.

The word *democracy* means rule by the people. In a democracy, ordinary people get to take part in making the decisions that affect them. These decisions are made in public through some process that
Involves public discussions. Sometimes, democracies make rules that put limits on an individual’s freedoms. For example, traffic rules limit your freedom to drive however and wherever you wish. Yet those rules are generally accepted because they improve public health and safety.

As I discuss in chapter 5 of Not Trivial, there are several different kinds of discussion, each of which serves a different purpose. The political discussions within a democracy deal with two kinds of questions: scientific questions (i.e., questions about what is true) and policy questions (i.e., questions about what should be done, and who should do it).

To make good policy decisions, the people must first find reliable answers to some scientific questions, so that they can predict what the effects of various policies would be. Then, they must use a process of negotiation to come to a consensus on what should be done, and by whom. In discussions about vaccination policy, we seem to get stuck on the scientific questions. Unfortunately, many people are ignoring the scientists. Too many of us are listening instead to attention-seeking celebrities and profit-seeking entrepreneurs instead of to professors.

To get reasonable answers to scientific questions, one must use facts and logic. As John Adams, who later became the second President of the United States, once wrote, “Facts are stubborn things; and whatever may be our wishes, our inclinations, or the dictates of our passion, they cannot alter the state of facts and evidence.” The rules of logic are also stubborn. When you have a given set of facts, the rules of logic sometimes lead to conclusions that you do not like. You may choose to deny the facts, but denial does not change reality.

Nonscientists often do not understand or appreciate what goes on in scientific debates. They may not understand that there are rules for deciding who wins, just as there are rules for deciding who wins a card game. Yet the rules in a card game were designed to make the game fun. Science is not a game, and the rules that scientists follow were not made up for fun. They were developed through a long and sometimes painful process of recognizing and correcting mistakes.

When people with no scientific training try to take part in scientific discussions, they often make errors of fact and errors in reasoning. They are simply unaware of many important facts. Nor do they know how to draw reasonable conclusions from the facts. In other words, they make mistakes because they lack knowledge and thinking skills. Yet because of their lack of knowledge and thinking skills, they cannot spot their own mistakes.

Of course, scientists face the same problem. Scientists don’t always know all the facts that they need to know. They can also make errors in reasoning. Yet the scientific community has ways to solve those problems. Scientists take part in scientific discussions so that they can share their knowledge with each other and correct each other’s mistakes. These discussions help scientists develop theories that provide a better description of reality, as well as finding better ways to solve practical problems.

Because of their knowledge and thinking skills, scientists can make important contributions to other kinds of discussions. For example, journalists often interview scientists when covering stories about scientific issues. Likewise, lawyers often hire scientists to serve as expert witnesses in court cases. Of course, judges don’t allow just anyone to serve as an expert witness. To serve as an expert witness in a court case, you generally have to have some sort of expertise. You need qualifications, such as special training and experience.

When journalists choose sources for an article about some scientific question, they should be just as picky as a judge. Unfortunately, journalists often use an approach called false balance, in which they interview some crank who has kooky, provocative views about some important topic and then provide a comment or two from a genuine expert, supposedly for balance. Although this approach may seem to be fair, it is misleading. It can give fools and liars far more publicity than they deserve. The fact that their comments are given at the top of the story even lets them outshine the real experts.

As I’ll explain in chapter 1, scientists are valuable members of a democratic society. Yet science itself is not democratic. Facts, being stubborn things, do not obey the will of the people. You cannot make something true by persuading the majority of the population to believe it. Nor is everyone created equal when it comes to a scientific debate. People who have dedicated their careers to studying a particular
The Rise of Scientific Medicine

There have always been people who refuse for religious reasons to have any medical treatment, including vaccination. But today, many people speak out against vaccination for what they claim are scientific reasons. At first, some of these people sound as if they might have valid concerns about a particular vaccine. Yet when you cross-examine them, or simply listen to them carefully, you often find that they are against all vaccinations, as a matter of principle. Often, they recommend some other kind of treatment, such as homeopathy or chiropractic, as an alternative to vaccination. Yet those “alternative” treatments have no effect on infections.

To understand why some people support vaccination while others oppose it, you need to understand the role that medical theories play in medical practice. To understand medical theories, you must think of medicine as a way to solve problems. When you have a problem, the approach that you take to solving it will depend on what you think the cause of the problem is.

Scientific discipline are likely to know far more than the average person about that subject. A wise person listens carefully to scientists.

To have a reasonable discussion about who should get what vaccines, you need to know something about history and biology. You also need to know something about the basic rules for how to have a reasonable discussion. In the following chapters, I’ll give you an overview of how scientific medicine arose. I’ll also explain how and why some popular alternative approaches to modern medicine were developed. I’ll also explain why you are usually better off listening to scientists than to uneducated people, at least when any sort of scientific question is involved.
Throughout most of human history, people looked to the supernatural to explain the cause of disease. People assumed that if you were sick, you were being attacked by evil spirits. Maybe a witch had cast a spell on you. Or maybe you were being punished by God. If you think that you are being attacked by evil spirits or witchcraft, you are likely to use some sort of magic to ward off evil. For help, you would turn to some sort of magician. If you think that you are being punished by God, you may beg for mercy or perhaps even try to strike some sort of bargain with God. For help, you would turn to a priest.

Midwives were the first healthcare professionals, but the first physicians were priests. Hippocrates, the ancient Greek who is considered the father of medicine, was probably a priest in a pagan temple. Hippocrates was born around 460 BC on the island of Kos, the site of an important asclepion, or temple to the Greek god Asclepius. People who were concerned about their health would make a pilgrimage to an asclepeion. Thus, the asclepeia came to serve as health spas and hospitals.

The ancient Greeks believed that Asclepius was the son of their sun god, Apollo. Both Apollo and Asclepius were called “the Healer.” The rod of Asclepius was a stick with a snake wound around it (Figure 1). It is used as a symbol of medicine to this day. Originally, the rod of Asclepius probably represented the treatment for a horrible disease called Guinea worm or dracunculiasis. Guinea worms are long parasitic worms that cause agonizingly painful sores on the legs. The worms have to be pulled slowly out of the skin by being wound around a stick. (As I’ll explain in chapter 19, these worms are on the verge of extinction as I write this book).

The caduceus, or herald’s staff, which has two snakes wrapped around a winged staff, has also been used to represent medicine (Figure 1). It originally represented the messenger god, Hermes (Mercury), who was the messenger of the Gods, as well as the god of commerce and thieves. Perhaps the staff of Asclepius should be used to symbolize the humanitarian aspects of healthcare, while the staff of Hermes should represent the profit motive of the healthcare industry.

In a military setting, the caduceus was carried by the messengers who were sent to negotiate peace terms. Thus, soldiers were taught that they should not kill anyone who was carrying the caduceus. Eventually, military doctors also started using the caduceus symbol, for protection. Today, the Red Cross or Red Crescent emblem is used to mark humanitarian and medical buildings and vehicles in battle zones.

The ancient Greeks believed that Asclepius had several daughters. One was Hygieia, the goddess of good health and cleanliness. Her name was the source of our word hygiene. Another of his daughters was Panacea, the goddess of universal remedy. Even today, the word panacea means a cure-all.

Eventually, some of the ancient Greek philosophers started to doubt the power and even the existence of their gods. Thus, many educated Greeks turned away from supernatural explanations for disease. Instead, they started to look for ordinary physical causes and practical cures. The people who took that approach to providing healthcare stopped being priests and started being physicians. One particular man, named Hippocrates, came to represent that approach to medicine. Thus, he is considered the Father of Medicine.

Hippocrates probably came from a priestly family, but his ideas about medicine were strictly nonreligious. He explained illness in terms
of ordinary physical causes, such as environment, diet, and lifestyle. According to legend, Hippocrates traveled all over the ancient Greek world teaching that idea to other physicians.

The idea that illness is the result of natural causes, as opposed to supernatural causes, would probably have made Hippocrates unpopular with some other priests, as well as with some of the secular authorities. If patients stopped believing that illness was the work of the gods, then priests would lose power and prestige. So would the secular authorities because religion would no longer serve the purpose of social control. Legend has it that the authorities were so angry with Hippocrates that they sent him to prison for 20 years.

While in prison, Hippocrates would have had a lot of time on his hands. According to legend, he used that time to write down his ideas about medicine. Many writings attributed to Hippocrates have survived to the present day. Many modern historians believe that Hippocrates was a real person, as opposed to a mythical character. However, nobody really knows which of the Hippocratic writings were really written by Hippocrates and which were written by his followers and their students. When modern-day people say that Hippocrates wrote something, they really mean that some anonymous Hippocratic author wrote it, not necessarily Hippocrates himself.

The Hippocratic writings make fascinating reading, especially for anyone with modern medical training. Hippocrates believed in careful, detailed observation of the patient’s condition and the course of the illness. As a result, the Hippocratic writings contain the oldest known descriptions of many disorders, such as migraine headache. (Of course, some of their medical knowledge may have come from older sources, especially from Egypt.)

The Hippocrates thought that all illness should be explained in terms of ordinary physical causes. Nowhere in any of the Hippocratic writings do you find any suggestion that any disease is the result of a magical or supernatural cause. In the discussion of epilepsy, the Hippocratic author even complained that people turn to supernatural explanations out of ignorance.

Hippocrates was on the right track in saying that we should search for the physical causes of illness. Unfortunately, back then nobody knew enough about biology or chemistry to figure out what those physical causes actually were.

Although the ancient Greeks knew about air, oxygen had not yet been discovered. There were no microscopes back then, so nobody knew that the body is made up of cells, and no one had any idea that bacteria or viruses exist. Although people knew that children tend to look like their parents, nobody knew about genes or chromosomes. Although people knew that the heart and blood existed, they had no idea that the heart pushed the blood around a circular path: from the heart out to the rest of the body and then back to the heart. Even some of the ancient Greek ideas about basic human anatomy were incorrect because there was a taboo against doing dissections of human remains. As a result, doctors didn’t do autopsies to figure out why a patient died. So even if someone wanted to explain illness in terms of natural phenomena, the explanations they came up with were usually wrong.

Although Hippocrates and his followers stressed observation, they also had theories to help them make sense of what they saw and to guide them in choosing treatments. Their main theory was based on a very primitive theory of chemistry. Like modern chemists, the Hippocratics believed that all matter is made up of invisibly small particles called atoms. However, the Hippocratics thought that there were only four elements, which meant four kinds of atoms: earth, water, air, and fire. To a modern chemist, these “elements” actually represent three phases of matter (solid, liquid, and gas) plus energy. Modern scientists have identified 118 different elements.

Hippocrates believed that his four elements were associated with four basic physical properties: hotness and coldness, wetness and dryness. The four elements gave these properties to four basic bodily fluids, called the humors: blood, yellow bile, black bile, and phlegm. One of the major goals of Hippocratic medicine was to restore the normal balance among these four humors within the body, thus allowing the body to heal itself.
Besides fire, which represented heat, the Greeks were aware of another kind of energy, one that enabled a body to move. They referred to this kinetic form of energy as *pneuma*, which meant breath or spirit. *Pneuma* represented the breath of life. The ancient Greeks believed that *pneuma* flowed through the arteries and nerves and made the body move. When people die, they stop breathing. Thus, the Greeks believed that *pneuma* had something to do with the soul.

This idea of *pneuma* is strikingly similar to what is called *chi* in traditional Chinese medicine or *prana* in Ayurvedic medicine. In other words, the main concepts of these Eastern medical systems used to be central to Western medicine. However, modern medicine discarded these concepts when science started to give us better explanations of how the body works.

In ancient times, nobody knew the real causes of disease. Thus, they could not explain why some diseases occurred only in certain times and places. An endemic disease is a disease that occurs in some places but not in others. One example is malaria, which tended to occur only in swampy areas. If you drained a swamp, the people who lived in that area stopped getting malaria.

The ancients believed that malaria was caused by the bad smells that come from a swamp. The word *malaria* literally meant bad air. Galen believed that this bad air, or miasma, was a major cause of disease. He believed that when meat or plants rot, they produce a miasma that could make people sick. Sick people, in turn, could generate miasma, which explained how they could pass a disease on to other people.

Epidemic diseases, which were diseases that occurred during some periods of time but not in others, were also a puzzle to ancient medical thinkers. What could cause a major outbreak of disease, such as an epidemic of smallpox or the Black Death? To explain epidemics, many medieval medical thinkers, particularly in the Islamic world, turned to astrology.

It actually made sense that some alignments of the heavenly bodies could produce miasma that caused epidemic diseases. After all, cold and flu season occurs in the fall and winter, when the sun passed through the constellations of Libra through Ares. Today, some
epidemiologists think that the sun does matter. They suspect that cold and flu season in Europe and North America results from lots of people having low levels of vitamin D, the sunshine vitamin, during the winter months.

In 1546, an Italian physician named Girolamo Fracastoro came up with a new explanation for why some diseases seem to spread from person to person. He thought that some diseases are caused by particles that are too small to be seen. These particles could be transferred from person to person, either by direct contact or by some object that the sick person had touched. The particles could even spread through the air for a considerable distance. These particles could explain why some diseases seem to be contagious. The best way to prevent the spread of many contagious diseases was to quarantine the sick, which originally meant to separate them from other people for forty days.

Doctors and nurses can accidentally spread disease from one patient to another, especially if they don’t wash their hands between patients. One of the first doctors to recognize that problem was Ignaz Semmelweis, who had been put in charge of obstetrics at Vienna General Hospital in 1847.

At that time, the doctors at Vienna General Hospital had just started doing autopsies on patients who died in hospital. At the same time, the death rate from a terrible disease called childbed fever rose dramatically among the women who had just given birth at the hospital. In some months, as many as 30% of the maternity patients died. Semmelweis noticed that the death rate was much higher among the women whose babies had been delivered by doctors, as opposed to midwives. After Semmelweis started making the doctors wash their hands, the death rate among the doctors’ maternity patients dropped to about 1%.

Many doctors refused to follow Semmelweis’ advice because it did not fit in with any of Galen’s theories. Nor did the scientists of the day know what kinds of particles could cause disease. More than 150 years earlier, a Dutch linen merchant named Anthonie van Leeuwenhoek had discovered the existence of bacteria by looking at samples of pond water and scrapings from his own teeth under a powerful homemade lens. Yet nobody knew what bacteria were, or where they came from. It wasn’t until the second half of the 19th century that scientists proved that some bacteria cause disease.

The question of where bacteria come from was hard to answer. Do bacteria just appear, all by themselves, whenever the conditions are right? For example, ice crystals will form on a damp windowpane when the film of water freezes. Ice crystals aren’t the descendants of other ice crystals. Instead, the water just turns into ice crystals when the temperature drops below the freezing point.

For thousands of years, people thought that certain kinds of living things arose in a similar way. For example, they thought that rotting meat naturally turns into maggots. This theory was called spontaneous generation. Then, in 1668, an Italian physician named Francesco Redi showed that maggots would appear on rotting meat only if flies had laid eggs on it. The maggots would then become flies, which would then mate and lay eggs, and the whole cycle would repeat itself. Eventually, scientists realized that all living plants and animals are descended from parents of the same species. All living things are part of a family tree that stretches back to the dawn of life. This theory is called univocal generation.

In 1859, a young French chemist named Louis Pasteur showed that bacteria also came from other living bacteria. He boiled some beef broth to kill all the bacteria. Then, he found that bacteria grew only in the broth that was exposed to dust from the air, which carried live bacteria with it. Unless the broth contained live bacteria, no bacteria would grow. That’s why canned food doesn’t start to rot until you open the can.

Pasteur figured that if bacteria could cause meat to rot, they could also cause disease. So did a British surgeon named James Lister. Lister started using carbolic acid as an antiseptic in wounds. He also sprayed a mist of carbolic acid in the air in the operating room. As a result, a lot fewer patients died of infection. This practice was called antiseptic surgery. Back then, many doctors thought that pus and other signs of infection were a natural and even beneficial part of the healing process. Nowadays, doctors and nurses go to great lengths to keep wounds from becoming infected.
The germ theory of disease is the idea that some diseases result from an infection with a particular germ, such as a bacterium or a fungus. (It doesn’t mean that all diseases are the result of infection.) In 1867, Pasteur showed that two diseases that were killing silkworms were infectious. These diseases could be prevented by keeping the healthy silkworms separate from anything that had been contaminated by sick ones.

In 1873, a Norwegian physician named Armauer Hansen became the first person to link a particular human disease to a particular bacterium. He showed that leprosy is due to infection with a bacillus (rod-shaped bacterium) called Mycobacterium leprae. In 1875, a German physician named Robert Koch proved that anthrax, a disease that can affect humans or animals, is caused by a bacillus called Bacillus anthracis. In 1882, Koch proved that tuberculosis is the result of infection with the tubercle bacillus: Mycobacterium tuberculosis.

Pasteur knew that rabies is contagious. Rabid animals can spread the disease to other animals and to human beings by biting them. Pasteur guessed correctly that rabies is due to some germ in the rabid animal’s saliva. In the 1880s, Pasteur developed an effective vaccine to prevent rabies. However, he couldn’t isolate the rabies germ. So he concluded that it is simply too small to be seen through his microscope. Later on, other researchers found that several other infectious diseases, including yellow fever, smallpox, and polio, also had to be the result of germs that are too small to be seen through an ordinary microscope. Today, those germs are called viruses.

Although bacteria are living things, viruses are not. As I’ll explain in more detail in chapter 12, a virus is not a living thing. A virus is a thing that was made by a living cell. A virus is just a set of genes wrapped up in a delivery system. If those viral genes are brought into a living cell, the cell may follow the instructions encoded in those genes. Those viral genes tell the cell to make new copies of that virus, just as a computer virus tells a computer to copy and spread the computer virus.

There are millions and millions of species of bacteria, and who knows how many different kinds of viruses. However, most bacteria and viruses pose no threat whatsoever to human health. The inner and outer surfaces of healthy people’s bodies are simply teeming with bacteria. To figure out whether a particular bacterium is responsible for causing a particular disease, Robert Koch worked out four rules of thumb, which are called Koch’s postulates:

- The bacterium must be found in all organisms suffering from the disease but not in healthy organisms.
- The bacterium must be isolated from a diseased organism and grown in pure culture.
- The cultured bacterium should cause disease when introduced into a healthy organism.
- The same bacterium should be isolated again from the organism that became diseased after the bacterium was introduced.

To understand how and when to use Koch’s postulates, imagine that a particular germ is being tried for murder. Koch’s first and fourth postulates show that the germ was present at the scene of the crime. The second and third postulates help to rule out other suspects. If all four of Koch’s postulates are met, you can be sure, beyond a reasonable doubt, that the germ is guilty of causing that disease.

Unfortunately, you cannot always get all of the evidence that you would like to have, whether in science or in a criminal case. Nevertheless, you might still have enough evidence to convict a suspect. Thus, you can sometimes still be confident that a particular germ causes a particular disease, even if one of Koch’s postulates hasn’t been met. Many people, especially antivaccination zealots and HIV denialists, misunderstand that point.

Each of Koch’s postulates poses some sort of technical or ethical problem. The biggest problem with the first postulate is diagnosis. How can you tell one disease from another? Many diseases that are caused by different germs have similar symptoms. For example, many different germs can cause an illness that looks like the common cold. Also, a particular germ can sometimes cause different symptoms in different patients. The classic example is the plague, which is caused by a bacterium called Yersinia pestis. This bacterium can cause three
There are two problems with Koch’s third postulate—one practical, the other moral. The practical problem is that it’s sometimes impossible to cause a particular disease in an experimental subject. Either the germ has become too weak to cause the disease, or the subject is already immune to it. For example, Pasteur had found that when he inoculated chickens with Pasteurella multocida, the bacillus that causes fowl cholera, the chickens always died within 48 hours. But after one of the cultures had been weakened by the summer heat, it no longer made the chickens sick. Instead, it made the chickens immune to fowl cholera. Thus, Pasteur discovered that dead or weakened bacteria could be used to make an effective vaccine. This discovery was a major advance in the development of vaccines.

The moral problem with Koch’s third postulate is that it would be not only morally wrong but illegal to give a human being a potentially deadly infection, just to see if he or she gets sick. Some people argue that Koch’s third postulate was never fulfilled in the case of HIV and AIDS. Thus, they claim that we therefore don’t really know whether HIV causes AIDS. But when you cannot do an experiment, you can sometimes find natural experiments—situations where a treated group and a reasonably well-matched control group arose by accident—that provide the evidence you need.

The accidental contamination of blood products with HIV set up a natural experiment. After HIV testing became available, scientists tested the stored samples of blood products that had been given to patients. This testing showed that patients got AIDS from blood products only if those blood products had been contaminated with HIV.

Many nonscientists and even a few cranks within the scientific community have insisted that HIV does not cause AIDS. They may admit that AIDS patients are often infected with HIV, but they insist that the HIV itself is harmless. Instead, they believe that AIDS is due to other cofactors. In reality, there are always numerous factors that affect whether exposure to a particular germ will make someone sick.

Some people are naturally resistant to some infections. Sometimes, this natural resistance is genetic. Other people become immune to an infectious disease because they have already had it or a similar
infection. On the other hand, some people have poor resistance for one reason or another. For example, people with cystic fibrosis have thick, sticky mucus that is hard to clear from the lungs. As a result, they are at high risk for lung infections. Some infectious diseases, such as measles and AIDS, attack the immune system. Thus, they make a person more susceptible to other infections.

In other words, a germ is not always able to make a person sick. In those cases, exposure to that germ would not be a sufficient cause of that disease. Nevertheless, exposure to a particular germ is a necessary cause of some diseases. The smallpox virus is a necessary cause of smallpox. If you are never exposed to the smallpox virus, you will never get smallpox. Likewise, if you are never exposed to poliovirus, you will never get polio. The same goes for the viruses that cause measles, mumps, and rubella. The same goes for the bacterium that causes whooping cough. If you can eradicate those germs, you can achieve permanent 100% success in preventing those diseases.

The smallpox virus has something important in common with the measles, mumps, and rubella viruses. Each of those viruses causes infections only in human beings. There is no wild reservoir of these viruses to reinfect the human population. Once we stop the polio, measles, mumps, and rubella viruses from being transmitted from person to person, those viruses will become extinct. Thus, those diseases will never happen to anyone ever again. As a result, we can eliminate the diseases themselves and then avoid even the small risk associated with the vaccines to prevent them.

A worldwide vaccination campaign drove smallpox into extinction. Likewise, rinderpest, which was a measles-like disease of cattle, has been driven into extinction through a campaign to vaccinate cattle. As I write this, the Global Polio Eradication Initiative is about to eradicate polio from the face of the earth. Worldwide vaccination campaigns could drive measles, mumps, and rubella into extinction. Once those viruses have gone the way of the dodo bird, then nobody will have to be vaccinated against those diseases ever again.

Some bacterial diseases occur only in human beings. Vaccination has practically eliminated some of these diseases, at least in some geographic areas. For example, diphtheria was a major cause of death in the United States in 1900, but now it is practically nonexistent in the United States. Thus, the diphtheria vaccine has provided a great deal of protection for the entire population, even for the people who were never vaccinated. Unfortunately, major outbreaks of diphtheria occurred in the former Soviet Union in the 1990s, after vaccination coverage dropped. In the United States today, we are seeing outbreaks of whooping cough, especially in areas where many people are refusing to have their children vaccinated.

For thousands of years, human beings have been praying for deliverance from terrible plagues like smallpox and cholera. Over the past 200 years, the medical profession has learned how to provide this deliverance. People are still praying for an end to the AIDS epidemic.

When the AIDS epidemic broke out, it took scientists only a few years to prove that AIDS is caused by the human immunodeficiency virus (HIV), which is a retrovirus. HIV is similar to the feline leukemia virus (FeLV), which is a retrovirus that causes immune suppression in cats. Tragically, efforts to develop an effective vaccine against HIV have failed so far. Nevertheless, scientists have found ways for people to prevent the spread of the disease and have developed medications that dramatically improve the health and life expectancy of infected people.

Inexplicably, many influential people refused to accept that HIV causes AIDS or that the anti-AIDS medications save lives. Public health experts estimate that the South African government’s refusal to accept grants and free anti-AIDS drugs led to the avoidable deaths of a third of a million people. We live in an age when the biggest threat to our health is not germs per se but foolishness.
What Are Bacteria?

Bacteria are the smallest living things. They are also the most adaptable. In the movie *Jurassic Park*, one of the scientist characters explained that “life finds a way.” The forms of life that are the most likely to find a way to survive are bacteria. Some species of bacteria have found ways to live inside glaciers. Others have found ways to live in volcanic hot springs that are as caustic as battery acid and are hot enough to blister your skin. Thriving colonies of still other bacteria have been found in high-level nuclear waste. Of course, there are also many bacteria living in much more comfortable places, such as on and in our bodies.

Bacteria are so adaptable because they can evolve far more quickly than we can. Any of the cells of a person’s body could get a useful mutation. However, the mutation cannot be handed down to that person’s children unless it is in the cells that give rise to the sperm or egg cells. Even then, it would take many years for a baby who inherits that useful mutation to reproduce. In contrast, any bacterium that gets a useful mutation can divide. Some bacteria divide as...
living thing, consists of one single tiny cell. The plants and animals and fungi that are big enough to be seen with the naked eye are made up of collections of many large cells.

By the 1850s, scientists realized that all cells are the descendants of other living cells, which reproduce by splitting in two. For example, all of the cells in your body are the direct descendants of a single fertilized egg, which then split numerous times. Likewise, all bacteria are the descendants of other bacteria.

In a plant, each cell is surrounded by a fibrous shell called a cell wall. In contrast, no animal cells have a cell wall (Figure 4). Fungi and bacteria also have cell walls, so at first it made sense to classify fungi and bacteria as plants. Yet when you look at the structure and chemistry of the cell walls, it becomes clear that plant cell walls are completely different from fungal cell walls, and both the plant and fungal cell walls are completely different from bacterial cell walls.

Figure 4. The cells of plants, animals, and fungi are relatively large and complex. Note that animal cells do not have a cell wall or chloroplasts. The cells of bacteria are small and simple. The flagella that are found on some animal cells and on the reproductive cells of plants are structurally different from the flagella found on bacteria.
The cells of animals, plants, and fungi differ from bacteria in an important way. When you look at the cells of an animal, plant, or fungus through an ordinary microscope, you can usually see a single big dot inside. That dot is called the nucleus, which is the Latin word for kernel. The nucleus contains chromosomes, which contain the cell’s genes. The DNA is a long molecule. In the chromosomes of plants and animals, the DNA is twisted around spools made out of small proteins called histones.

Most of the cells in your body contain exactly one nucleus. Some kinds of cells, such as liver cells and some cancer cells, have more than one nucleus. Red blood cells start off with a nucleus, but their nucleus disappears as they mature.

All of the organisms that have a proper nucleus in their cells — animals, plants, and fungi, plus lots of single-celled organisms — have now been lumped together in a group called the Eukarya, which comes from the Greek for “having a good kernel.” The single-celled organisms that never have a proper nucleus are called prokaryotes (“before having a kernel”) because prokaryotes appeared before eukaryotes.

All eukaryotes have some important things in common. Each of their cells has internal membranes that divide its interior into separate compartments. In contrast, the interior of a prokaryote cell is just one open compartment. In other words, a eukaryote cell is like a sprawling mansion with many rooms, while a prokaryote cell is like a small, one-room cabin. Like eukaryotes, the prokaryotes have genes in the form of DNA. However, the prokaryote DNA is not packaged in chromosomes.

Prokaryotes may look simple, but they are incredibly diverse. As you can see from Figure 5, most of the varieties of living things are really prokaryotes. As microbiology advanced, many scientists started to believe that the most important division among living things was not between animals and plants. It was between two different kinds of prokaryote. The eukaryotes — animals, plants, fungi, etc. — are really just an offshoot of a strange group of prokaryotes called archaea.

The archaea have something important in common with the eukaryotes: the histones associated with their DNA. Although the archaea don’t really have proper chromosomes like those you’d find in an animal cell or plant cell, they do have some histones bound to their DNA.

Bacteria have genes made of DNA, but they don’t have histones. Instead, most of their DNA is in a big, naked, tangled circle called a nucleoid. Bacteria can also have smaller rings of DNA called plasmids. Bacteria can pass these plasmids to other bacteria, even to unrelated bacteria. That’s how the genes for antibiotic resistance can jump from one strain of bacteria to another, and even from one species of bacteria to an unrelated species.

Of course, not all of a eukaryote’s DNA is found in the nuclei of its cells. All eukaryotic cells contain tiny structures called mitochondria. Each mitochondrion has its own DNA. Plant cells have

Figure 5. All of the plants, animals, and fungi that we can see around us are members of the Eukarya, which make up only a tiny portion of the tree of life. Most of the living things on planet Earth are actually bacteria. Note that the gram-positive bacteria are all related to each other. Data from Letunic and Bork (2006) Bioinformatics 23(1):127-128.
mitochondria. Plant cells also have chloroplasts, which also have their own DNA. Mitochondria and chloroplasts look a lot like bacteria, but without cell walls (Figure 6).

Like bacterial DNA, mitochondrial DNA is in a naked ring, without histones. In fact, most microbiologists are now convinced that mitochondria and chloroplasts are descended from ancient bacteria that learned how to live inside an archaeon. These ancient bacteria and their archaeon host developed a symbiotic relationship, which means a relationship that is good for both parties. Mitochondria allow a cell to use oxygen to burn fuel. Chloroplasts enable plants to do photosynthesis.

As you can see from Figure 5, bacteria are really the most diverse and plentiful form of life on Earth. They are everywhere, and they do many important things. We could not survive without them. There are also many bacteria on your body. You have more bacteria in your mouth than there are human beings on the planet. You have more bacteria on your body’s outer and inner surfaces—mainly inside your intestines—than you have cells in your body. This idea might be frightening to someone who is afraid of germs. However, it helps to explain a puzzling fact about the history of medicine.

Scientists got their first glimpse of bacteria in the 1670s, when Anthonie van Leeuwenhoek used his powerful handmade lenses to look at things like pond water or the scrapings from his own teeth. As I explained in chapter 2, it took nearly 200 years for doctors to realize that some bacteria cause disease.

Why did it take so long for scientists to come up with the germ theory of disease? I think that it’s because the vast majority of bacteria are harmless. Only a few species of bacteria are likely to cause disease. Before scientists could prove that certain bacteria could make you sick, they had to figure out ways to tell one kind of bacterium from another. The problem is that most bacteria look pretty much alike. Under a microscope, they look like little dots or squiggles, if you can see them at all.

Figure 6. Bacterial cells are much smaller and simpler than the cells of a plant or an animal. The chloroplasts inside plant cells and the mitochondria inside plant and animal cells are probably the descendants of ancient bacteria.
We human beings tend to be highly visual creatures. We mainly use visual clues—such as size, shape, and color—to tell one kind of plant or animal from another. But we cannot see bacteria at all. They are simply too small to be seen with the naked eye. To see them, you need a microscope. Even so, you may need to use special stains to make them visible.

Staining

Stains can also help you tell different kinds of bacteria apart. The stains reveal not only the bacterium’s shape but also its chemical makeup. Often, the first step in identifying a bacterium is to use a multistep staining procedure called Gram staining (Figure 7).

Some bacteria have a thick, porous cell wall that takes up lots of crystal violet stain, which turns them dark purple. Treating these stained cells with iodine traps the crystal violet in those thick cell walls. Thus, they remain dark purple even after being washed with a mixture...
of alcohol and acetone. The bacteria that remain dark purple after being washed with alcohol and acetone are called gram-positive (Figure 8). DNA studies eventually showed that the gram-positive organisms make up an important branch of the bacterial family tree (Figure 5).


Other bacteria are surrounded by an outer membrane that protects the cell wall from the crystal violet. (This membrane is in addition to the regular cell membrane that is inside the cell wall.) However, this outer membrane would be washed away by the mixture of alcohol and acetone. Then, they can be counterstained pink with safranin. They are called gram-negative bacteria (Figure 8).

Some bacteria have a fatty substance called mycolic acid in their cell wall. As a result, they are hard to stain with crystal violet but also hard to decolorize with an acid-alcohol solution. Thus, these bacteria are described as acid-fast. They turn a light purple color from the Gram staining procedure. To get a better look at them, you need to use some other staining technique, such as a Ziehl-Neelsen stain, which turns them bright red.


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**Figure 7.** A Gram staining procedure involves five steps: (1) Heat is used to make the bacteria stick to a microscope slide. (2) The bacteria are treated with a dark purple or blue dye. (3) Iodine is used to fix the dye. (4) The dye is rinsed off with a mixture of alcohol and acetone, but the dark purple stain stays in the gram-positive organisms because of the way their cell walls are built. (5) A pink counterstain is used to make the decolorized gram-negative bacteria show up.

**Figure 8.** Gram-positive bacteria have a thick layer of peptidoglycan in their cell walls. Gram-negative bacteria have a thinner cell wall that is surrounded by an outer membrane.

**Bacterial Shape (Morphology)**

Stains make it easier to see a bacterium’s shape, which is called its morphology (Figure 9). Most bacteria look like punctuation marks. A bacterium that looks like a period is called a coccus, which means berry. A bacterium that looks like a hyphen or dash is called a bacillus or a rod. Some rods look a bit twisted. The ones that have a slight twist look like commas. The comma-shaped bacteria are called vibrios. The long spiral bacteria that look like corkscrews are called spirochetes.
from the genus *Staphylococcus* can split along different axes. Thus, they tend to form disorderedly clusters that look like bunches of grapes. When the rod-shaped bacteria (bacilli) divide, they never split lengthwise. That’s why they can form end-to-end pairs (diplobacilli) and chains (streptobacilli), but never divide to form side-by-side stacks.

**Motility**

Another clue to a bacterium’s identity is its motility, which means whether it can move around by itself. Some bacteria have a whip-like extension called a flagellum that acts like a tiny propeller (Figure 10). Some bacteria have one flagellum. Others have exactly two flagella—one flagellum at either end. Still others have many flagella. Some of those bacteria have all of their flagella in a single tuft. Others have flagella scattered all over their surface. When the flagella rotate counterclockwise, the flagella bunch together and the bacterium “runs” in a particular direction. When the flagella rotate clockwise, the bacterium tumbles around and changes direction.

Some kinds of bacteria always seem to have a consistent shape, no matter what. In other words, they are monomorphic, which means one shape. Other kinds of bacteria can take on a different shape under different environmental conditions. Sometimes, they vary in shape even within the same culture. The bacteria that can take on more than one overall shape are called pleomorphic (sometimes spelled pleimorphic) or polymorphic.

Sometimes, the way that bacteria divide gives you a clue to their identity. The cocci that are found in pairs are commonly called diplococci. Bacteria from the genus *Streptococcus* tend to divide along one axis. As a result, they tend to form long chains. In contrast, bacteria

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**Figure 9.** The common shapes of bacteria. A coccus is a round bacterium. Some species of round bacteria can often be found in pairs (diplococci), others in bunches (staphylococci), and still others in chains (streptococci). A rod-shaped bacterium is called a bacillus. Bacilli are sometimes found in chains. Some bacteria are spiral.

**Figure 10.** Some bacteria have flagella that serve as propellers.
Spore Formation

Another important clue to a bacterium’s identity is how it reacts to conditions that it doesn't like. Some bacteria, like the one that causes anthrax, can convert themselves into tough, dried-up spores that can survive for many years until conditions improve. Spores can be extremely hard to kill because they resist most ordinary household cleaning products.

Response to Culture Conditions

One of the most important clues to the identity of a bacterium is what it takes to get that bacterium to grow in the laboratory, and what the colonies look like when they do grow in the laboratory. Bacteria that are hard to grow in a laboratory are called fastidious. They may need special nutrients, a low-oxygen environment, or just a long time to grow.

As I explained in chapter 10, bacteria have found ways to adapt to many different habitats. Some of these habitats are rich in oxygen, but others have practically no oxygen. Aerobic bacteria need oxygen in the form of O\textsubscript{2}, just as the cells of our own body do. Anaerobic bacteria do not need O\textsubscript{2}. For energy, many of them simply split glucose molecules into lactic acid, which is a reaction that does not consume oxygen. Bacteria that can switch back and forth between an aerobic or anaerobic lifestyle are called facultative aerobes or facultative anaerobes, depending on which lifestyle they prefer.

Microaerophilic bacteria need oxygen in the form of O\textsubscript{2}, but they need O\textsubscript{2} levels that are far lower than what is found in the atmosphere. Some microaerophilic bacteria are capnophiles, which means that they need a high concentration of carbon dioxide. Even fairly low O\textsubscript{2} levels are toxic to some anaerobic bacteria.

If you grow bacteria in a test tube full of liquid, aerobes would end up clustered at the top, where there's plenty of oxygen. The anaerobes would be found at the bottom, as far away from the atmosphere as possible. The facultative aerobes and facultative anaerobes would be found all through the liquid.

In your body, the aerobic bacteria tend to be found in places where there is plenty of oxygen, such as on your skin or in your upper respiratory tract and lungs. Facultative anaerobes, on the other hand, can live on the skin but can then invade deeper structures. Anaerobic bacteria tend to thrive in places where there isn't much oxygen. Some anaerobic bacteria are normal residents of the insides of your intestines. Some of these bacteria provide useful services, such as helping you digest your food and producing important nutrients, such as vitamin K.

Another clue to the identity of a bacterium is the kind of nutrients it needs to survive. Some bacteria live independently like green plants. They make their own fuel by using the energy from sunlight to make sugar out of carbon dioxide and water. Then, they make everything else they need from the sugar, some ammonia, and some minerals. In contrast, most of the bacteria that are likely to cause disease in a human being or other animal are so highly adapted to a parasitic lifestyle that they need to get some complicated nutrients from an animal host. One way to tell different species and strains of bacteria apart is to see what they can and cannot digest, and what they can and cannot do without. For that purpose, you can use special culture media.

Some bacteria have become so highly adapted to a parasitic lifestyle that they cannot reproduce outside of some other living cell. These bacteria are called obligate intracellular parasites. One example is the syphilis spirochete. Until scientists figured out how to grow human cells in cell culture, there was no way to grow syphilis spirochetes in a laboratory. Yet to keep a culture of human cells alive, you may have to treat it with serum from animal blood, thus raising the risk that the culture will become contaminated with some other bacteria or virus. Mycobacterium leprae, which is the cause of leprosy, is even more finicky. Scientists cannot yet grow it even in cell culture. It can be grown only in armadillos or in specially bred mice.

When bacteria do grow in a laboratory, the colonies tend to take on a particular appearance, which helps in identifying them. Alexander Fleming used to create pictures by using bacteria as paints. He’d smear the various bacteria on the surface of the culture medium in a Petri dish and then watch the picture emerge as the bacteria grew. Fleming eventually noticed that some of his bacterial cultures would not grow anywhere near a mold called Penicillium. The mold was making something that killed bacteria. That’s how he discovered penicillin.
Some bacterial strains are susceptible to penicillin or other antibiotics. Others are resistant to various antibiotics. The standard way to test their susceptibility is to put a disk of filter paper soaked with the antibiotic in the Petri dish with the bacteria. If there’s a clear zone around the disk, then the bacteria are susceptible to that antibiotic. If the bacteria can grow right up to the disk, they are resistant to the antibiotic. That finding usually means that the antibiotic will be useless in treating infections caused by that germ.

Streptococci all look practically the same under a microscope. When stained by the Gram staining technique, they show up as dark purple dots, often in pairs or chains. Yet some streptococci are dangerous, while others are part of the normal flora found in the mouth and throat of healthy people. To tell the different kinds of streptococci apart, scientists started by sorting them into three groups, according to how they look when grown on blood agar.

Streptococci are so adapted to living a parasitic lifestyle that they need some nutrients that come from some other living thing. As a result, they are generally grown in culture media that contain extracts from meat, plant materials, or yeast. In laboratories, they are generally grown on blood agar, which is a gel that contains red blood cells. Some streptococci release hydrogen peroxide, which turns the hemoglobin in the red blood cells green (alpha hemolysis). Thus, you’ll see a green area around and underneath the colonies of alpha-hemolytic streptococci that are grown on blood agar. Other streptococci produce enzymes that attack the cell membrane of the red blood cells, causing them to burst (beta-hemolysis). Thus, you’ll see a clear area in the blood agar around and under the colonies of beta-hemolytic streptococci. Still other streptococci have no effect on the red blood cells in the blood agar. They are called gamma-hemolytic streptococci.

There are several ways to identify the individual strains of a species of bacteria. One approach is to use an antibody-based test. Antibodies bind specifically to certain antigens. If you add something that contains that antigen to serum that contains those antibodies, the antibody-antigen complexes will stick together in clumps. The strains of bacteria that have a positive result from a particular antibody test make up a serotype.

**Typing**

Sometimes, antibody-based tests are useful for telling one species of bacteria from another. An American microbiologist named Rebecca Lancefield developed this method for sorting the beta-hemolytic species of streptococci into several groups, each of which contained one or more species. For example, group A were responsible for strep throat and rheumatic fever. Group B can cause pneumonia and meningitis in newborns. Group C cause a disease called strangles in horses. Antibody-based tests can also be used to identify particular strains of a single species of bacteria.

Some antibody-based tests use an antibody that has been bound to some fluorescent dye. This approach, which is called immunofluorescence, can show how a particular antigen is distributed in tissue. But since antibodies are too big to pass through cell membranes, this method cannot show what antigens are present inside a living cell.

Lately, researchers and even medical practitioners have been able to use DNA tests to figure out whether a particular bacterium is present, and to figure out how various species and strains of DNA are related to each other. The results of these studies are sometimes confusing because bacteria can swap genes with other, unrelated bacteria.

When microbiologists are trying to identify particular strains of some bacteria, such as *Haemophilus influenzae*, they look to see if the bacteria have a capsule. Some bacteria secrete a slimy substance that forms a protective capsule surrounding the cell. Some strains of *Haemophilus influenzae* produce a capsule, while others do not. This capsule generally does not take up stain very well. Thus, it appears as a pale halo around a stained cell.

Bacterial capsules are made up mainly of a polysaccharide, which is a chain of molecules of simple sugars. (In contrast, a protein is made up of a chain of amino acids.) A capsule helps a bacterium stick to surfaces, and it protects the bacterium from drying out. Thus, it helps the bacterium survive in the environment. The capsule can also serve as a shield that protects the bacterium from the immune system. That’s why the *Haemophilus influenzae* strains that have a capsule are far more dangerous than the strains that do not have a capsule.
How Bacteria Cause Disease

Many species of bacteria have found ways to survive on the inner or outer surfaces of the human body. Most of them cause no harm. Some of them are even beneficial. The bacteria that cause no harm are described as commensal. The word commensal comes from the Latin for “sharing a table.” The bacteria that actually provide some benefit to their host are called symbiotic, which came from the Greek for “living together.” The bacteria that cause disease are called pathogens, which literally means that they generate disease.

There are several different ways in which a bacterial infection can harm the body. Some bacteria directly attack the cells of the body, just as they would digest a piece of meat. Others release some harmful substance. For example, tooth decay is the result of acid produced mainly by a bacterium called Streptococcus mutans when it digests sugars in the mouth. That’s why it’s important to clean the sugars and starches from your teeth after you eat.

Some bacteria produce particularly dangerous substances called toxins. There are two basic kinds: exotoxins and endotoxins. Exotoxins...
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