Evolution


The time is 1925. The place is Dayton, Tennessee. In this Rhea County Courthouse the two most famous lawyers in America argued for and against a seventy-year-old scientific theory called evolution by natural selection.

On trial was a young high school science teacher named Tohn Scopes. Scopes, it was charged, taught his students that living things had evolved over millions of years from more primitive ancestors. Scopes believed and taught that man was descended from the monkeys, charged the prosecution's lawyer, the famous William Tennings Bryan.

Such a view, claimed Bryan, was absurd, was contrary to Holy Scriptures and was against the law in Tennessee. (In the popular press the trial was called "the monkey trial."

His opponent, the famous defense lawyer Clarence Darrow, argued that the Darwinian theory of evolution by natural selection was the most reasonable explanation for the variety and similarity of life on earth. Furthermore, said Darrow, the Tennessee law was unconstitutional since it prohibited free speech and put religion into the state's public schools.

The Scopes trial soon became an international sensation. Reporters from around the world crowded into the small town in Tennessee to record the drama for their readers. People in Dayton, and around the world, took sides in the controversy. A poll of the day found the courtroom equally divided, for and against evolution.

The trial's outcome was something of an anticlimax. Scopes was found guilty of breaking the Tennessee law against the teaching of evolution and was fined $100. The conviction was later overturned on a legal technicality. The sensational publicity of the trial, however, served to make a hero out of Scopes and hold Bryan and the cause he represented up to a good deal of ridicule. Bryan himself, broken in health and spirit, died in his sleep only a few days after the trial's verdict in a front parlor in Dayton.

The Scopes trial was the most famous. There have been many other conflicts the past 150 years over the scientific theory called evolution by natural selection. Some of these conflicts have been scientific ones, but many have been political and religious as well. Let's look at the world history of this idea, one of the handful of scientific concepts that are keys to scientific literacy today.

People from ancient times could not help noticing there was a great variety of plants and animals in the world. For the most part most people were too busy trying to survive in competition or cooperation with these other living creatures to give much thought to why there were so many. And to how they got to be the way they were. In some ways so like humans and in so many other ways so very different.
To those who did have the time or inclination to speculate about such questions, the most common answer was that a god or gods made them that way. Many also believed that the same god or gods made other living creatures to please and serve mankind.

In the ancient Ionian cities of Greece (now in ruins on the western coast of modern Turkey) some of the world's first scientist/philosophers dared to ask and answer questions like this in a different way.

Anaximander in 550 BC proposed a theory of evolution to explain the variety and likenesses among living things. All life, he said, has come from early life in the water. Over long periods of time, the water creatures crept out on the land, developed legs, then fur and finally human forms. Anaximander did not have much evidence to support his theory, nor did he have any ideas just how this kind of near miracle could have actually taken place.

One of the handicaps early thinkers had was massive ignorance about living things. They knew of the existence of only a tiny fraction of the variety of plants and animals that live on this earth. Aristotle, one of the first to invent a scientific classification, found room for about 500 species of animals. As late as 1600 only 6000 species of plants were known. By way of comparison, today over 2 million species of living things have been described.

In the high days of Renaissance science, when giants like Copernicus, Galileo and Isaac Newton were shaking the foundations of human knowledge about the earth and its place in the solar system, biology was in its infancy.

True, men like Vesalius and William Harvey were disproving some ancient misconceptions about the way the human body was built. The Dutch lens maker, Leeuwenhoek, was the first to view the wonder world of microscopic "little beasties." Still, little progress was made in developing any unifying ideas or in accurately describing and classifying knowledge about the complex living world.

In the eighteenth century, about the same time the American colonies were beginning to change into the United States, humankind's store of knowledge about this complex living world began to rapidly increase. Explorations into the far corners of the world were becoming more and more common. Many of the explorers were returning with specimens of new species of plants and of animals never before known to western scientists. And more and more men were becoming scientists. In those days there were few if any professional scientists- that is, people who made a living searching for answers to questions about nature. So it was that "amateur" scientists like our own Benjamin Franklin and Thomas Jefferson were among the first of the human race to devote their skills to the scientific study of living creatures.

One of the most important of the early pioneers was Carl Linnaeus of Sweden. Linnaeus, unlike most early scientists, was a poor boy. He hated school but he loved plants. As a young university student, poor and hungry and plagued with gout, he left on a field trip to
Lapland to collect plant and animal specimens. The 4,600 mile trip cost him only $100. The knowledge he gained on this trip paid off handsomely for all of us.

A few years after his trip in 1735 Linnaeus brought out his first book, Systema Naturae. It was a great scholarly hit and he became an instant celebrity. In this book he proposed a classification system for plants and animals that is still being used today.

All living things, suggested Linnaeus, should be grouped according to a natural and logical system he proposed. Each kind of living thing would be given a unique double name in internationally accepted Latin. First would be it's genus. Followed by its species. It was called a binomial nomenclature system.

Similar genera would be grouped together into families; families into orders; orders into classes; classes would be grouped into a few major phyla; and finally, phyla into kingdoms. It was a system that for the first time brought order and system into the study of the living world.

Linnaeus helped people see the reality of living species but he himself opposed the idea that living species had ever evolved from common ancestors. He saw his work of inventing and promoting the present classification system as the scholar's humble way of "tracing the footprints of the Creator."

One of the most important was a Frenchman, Georges Buffon. A charming, elegant man of great wealth, Buffon was able to devote his life to scientific study without worry of earning a living. He founded one of the first genuine biological research centers of the world, the Jardin de Roi (Garden of the King) in Paris. He is said to have started his work day at 6 a.m. each morning, taking two breaks each day to have his hair dressed and powdered. In between many love affairs and a few duels, he managed to write forty-four volumes of natural history. These volumes summarized all that was then known about the natural world. In some of these volumes he anticipated many of the ideas of Darwin and later evolutionists, but he never quite put together a convincing theory to explain the mechanisms of evolution.

The books were convincing enough to the religious authorities, however. They brought him before the Syndic of the Sorbonne in 1751 where he was commanded to withdraw portions of his books that seemed to contradict Holy Scriptures. One of the parts the religious authorities most objected to was Buffon's estimate of the age of the earth as on the order of 100,000 years. Biblical doctrine held that the earth was created in 4004 B.C.

Another frenchman, Jean Baptiste Lamarck, built on the foundations laid by Buffon to construct one of the first fully formed, genuinely scientific theories of evolution. As poor as Buffon was rich, Lamarck took over the Jardin de Roi when it became the Jardin des Plantes after the French Revolution. (Which revolution was also executed Buffon's aristocratic family.) Teaching himself zoology after the age of fifty, Lamarck proposed a theory of evolution with he said reflected the natural order of animals in nature. It's key ideas were two: nature has an innate tendency to evolve in the direction of increasing
complexity, and acquired characteristics will be passed on to offspring. In this way nature will slowly move toward increasing variety and complexity to fill up all the niches in the living world.

Lamarck also has the distinction of being the first to coin and use the world "biology."

Paradoxically, one of the Lamarck's most critical scientific opponents, the anti-evolutionist Georges Cuvier, laid even more important groundwork than did Lamarck for the later flowering of the Darwinian evolution theory.

Cuvier worked at the same Museum of Natural History in Paris in the late eighteenth and early nineteenth century. He is credited with founding the science of paleontology- the study of plant and animal fossils.

Before Cuvier, fossils were known but little understood. The most common view was that fossils were freaks of nature placed there to amuse and mystify numans. Cuvier spent many years systematically studying fossils found in the limestone deposits around Paris, as well as those brought to the Museum from all over the world. He compared the forms left in the rocks with the anatomical structures of living creatures of his day. He became the world expert in reconstructing an entire animal from a few fossil bones. And he concluded from his study that fossils were prints of former creatures, prints that had been made in great catastrophes of the past, the greatest of which was the flood described in the Bible when Noah built his ark.

The opposite geological view was taken by the Scotsman generally given credit as being the father of modern geology, James Hutton. Hutton viewed the earth as having no "vestige of a beginning, no prospect of an end." He saw earth as changing in the past, changing today and changing in the future. These changes occured very slowly but surely over very long periods of time from the same geological processes you could see happening today: mountain building, erosion, volcanoes and earthquakes.

Hutton's ideas were advanced and popularized by Charles Lyell, whose book Principles of Geology became the first classic work in geology and an important influence on biology as well.

By the mid-nineteenth century ideas about the possible evolution of living forms were widespread, but no one had yet convincingly demonstrated how it could have happened. The man deserving the most credit for doing so was an English gentleman, Charles Darwin.

Darwin as a young man was not considered promising. His father once told him "you care for nothing but shooting, dogs and rat-catching, and you will be a disgrace to yourself and your family." When he got the chance to go on a round-the-world voyage as a young unpaid naturalist he snapped up the opportunity. The rest is history. Darwin's five-year voyage of discovery on HMS Beagle changed the world.
Here is the way he cautiously, but accurately, summarized the voyage in the first sentence of one of the most famous works of science of all time, On The Origin of Species by Means of Natural Selection.

"When on board HMS Beagle, I was struck with certain facts in the distribution of the organic beings inhabiting South America, and in the geological relations of the present to the past inhabitants of that continent. These facts seemed to throw some light on the origin of species-that mystery of mysteries."

When Darwin got back to England his health was broken. He married, though, and had a large family. Fortunately he inherited wealth from his family and did not need to earn a living. Instead he settled in a country home in Down, just south of London to a life of quiet study.

On his daily walks behind the house overlooking the quiet English countryside Darwin gradually pieced together his theory of evolution by natural selection, the theory of evolution that in broad outline is still accepted today as one of the bedrocks of modern biology.

As so often happens in science, at almost the same time another man was coming to much the same theory. That man was Alfred Russel Wallace. In outline Darwin and Wallace's theories were almost identical and surprisingly simple. In nature, they said, living creatures have more offspring than can possibly survive. The result is a struggle for existence. Since offspring vary, some will be more fit than others to survive. These survivors will pass on their useful traits to their offspring. Thus, in time, nature will select the most fit to survive. And, much as a gardener artificially selects traits he wants to survive in his plants, or as a cattle breeder selects traits he wants in his cattle, nature's selections will create whole new kinds of living things. New species.

Darwin's book On the Origin of Species by Means of Natural Selection and his following book The Descent of Man piled one piece of evidence on another to illustrate and support his theory. And this evidence was so overwhelming it convinced most scientists all over the world.

Not everyone was convinced of course. In his day or in ours. In his day Darwin was ridiculed unmercifully from the pulpit and in the popular press. Also from some scientists.

Waxing and waning controversy over evolution has continued in our own day. Most scientists and many people of all faiths now accept the Darwinian theory of natural selection in broad outline. Some will add, however, that behind the scenes of organic evolution, it is God who is responsible for the living ascent, and most especially for the human soul. Others hold to a literal interpretation of the Bible and insist that all species were created at one time, with many being destroyed in one great catastrophe, the Biblical flood.
Some of these fundamentalist Christians have recently organized to search for scientific support for their Creationist views. They have also initiated court suits and legislative bills to force the public schools to give equal time to Creationist points of view.

Within the scientific community, too, there is disagreement about evolution. Not about the fact of evolution but about the details of natural selection.

And certainly of all scientific theories, the theory of evolution by natural selection has not only been the most controversial for the general public, it has also spawned the most varied social and political spins. Capitalism, socialism, communism, fascism, pacifism, manifest destiny, progressive education and more. All claim descent and support from the theory of evolution by natural selection of Charles Darwin and Alfred Russel Wallace.

Who is right? Who is wrong? Some say it is hopeless, we can never know these things. Others say we already do know, and it is this way.

Read on to Part Two of this program to learn details of present day evolution theory and of the controversies that accompany it.

Part 2: Evolution by Natural Selection

"Glory be to God for dappled things
for skies of couple-color as a brindled cow;
for rose-mores all in stipple upon trout that swim;
fresh-firecoal chestnut falls, finches wings ...
Whatever is fickle, freckled (who knows how?)
with swift, slow; sweet, sour; adazzle, dim;
He fathers forth whose beauty is past change;
Praise Him!"

That's how the poet, Jesuit priest and classical scholar, Gerard Manley Hopkins, celebrated the living world in 1877.

The same living world that his neighbor, Charles Darwin, English gentleman, father and scientist, had just explained (and celebrated) in two books that have become classics of science, *On the Origin of Species by Natural Selection*, and *Descent of Man*.

To understand the differences (and the likenesses) between these two approaches to truth, let's first look at Darwin's contribution. His theory of evolution by natural selection is one of a small number of key scientific concepts needed to make sense of our modern world.

There are over two million different species of plants and animals on earth today. Why are there so many? And why, despite this incredible variety, are all living things so much alike in their basic chemistry? Alike in their living structures and alike in their ways of surviving and reproducing?
And finally, how are today's living things related to those other living things whose fossil remains are found so abundantly all over the world?

The theory of evolution by natural selection answers all of these questions this way:

1. Living creatures have more offspring than can survive.

2. There is variation in these offspring.

3. Some variations give an advantage and some make for a disadvantage in an inevitable struggle for survival.

4. The more fit will survive and pass on their desirable traits to their offspring.

5. In this way living things will change. Given enough time, whole new species of living things will evolve upon this fruitful earth.

It sounds simple. And it is. That is part of the beauty of any good scientific theory. It accounts for a wide range of individual events, using a bare minimum of general principles. Simple or not, what evidence is there to support this theory?

Answer. A great great deal. And from many many different scientific disciplines.

First, and perhaps most important, there is the fossil record itself, nature's history book.

Fossils are the records in stone inadvertently left by living creatures of the past. Some are imprints of leaves, footprints, bones or droppings that have been covered over by sand or mud, and hardened into rocks that have survived for millions of years.

Sometimes we have actual fragments of plant and animal parts- pollen grains, teeth, bones, etc. Comparing these fragments to other similar structures in living organisms today, and with the knowledge that modern anatomy, physiology, geology, physics and biochemistry can provide, paleontologists have been able to construct a record of life in the past, as remarkable for its detail as for its drama.

Here are some highlights of that record—that world history—that are generally agreed upon by almost all experts who have carefully studied the fossil evidence.

The oldest fossils we have been able to find and identify come from rocks that were formed about seven hundred million years ago. In those days life was only found in the ocean. It apparently had been that way for over three billion years before that.

During that three billion years, however, life had branched, had changed, had evolved into many thousands, perhaps millions of different species. Each species had its own particular skill, its own particular advantage in the life struggle.
Some species developed a chemical process to make use of direct sunlight as a source of life energy. Today we call that process photosynthesis. These organisms were the ancestors of all our modern plants.

Some species developed ways of moving, of capturing food, of digesting food, of sensing light, heat and sound. These organisms in the ocean were the ancestors of our modern animals, fish, frogs, grizzly bears and human beings.

One of the clearest proofs we have that all of us, oak trees to frogs to human beings, have evolved from these common ancestors in the primeval ocean is the astonishing similarity in all of our life chemistries.

Whether you happen to be an oak tree or a frog or a human being, if we chemically analyze what you are made of, we find the same basic elements, compounds and mixtures. And always in very similar saltwater suspensions!

Most amazing of all, that saltwater suspension is very similar to the saltwater content of the ancient ocean! It can give you an eerie feeling: to taste your tears, or the sweat from your brow, or the blood from your cut finger, and suddenly realize that the salty taste comes from the "ocean" you still carry around inside you. The same ocean your single-celled ancestors lived in so long long ago!!!

Sometime around six hundred million years ago the seas began to teem with many-celled creatures. Cells had learned to clump together, and to specialize. And to make strange looking creatures like trilobites, snails and sea scorpions. Sometime around six hundred million years ago the seas began to teem with many-celled creatures. Cells had learned to clump together, and to specialize. And to make strange looking creatures like trilobites, snails and sea scorpions.

Another hundred million years go by and the variety increases. We find fossils of creatures that are direct ancestors to modern octopus, squid and horseshoe crab. Wait another hundred million years and the first vertebrates- animals with backbones- appear.

About four hundred million years ago life first began to take the giant step onto land. Plants were the first pioneers, creeping out in inconspicuous ways like modern rockhugging algae, mosses and liverworts. Animals followed. Insects, scorpions, and finally the first land vertebrates, lungfish and amphibians.

When we trace life history this way, it is not just imaginative speculation. We have millions on millions of fossil imprints of these creatures. And we have many ways of geologically dating the rocks these fossils are found in. Radioactive decay, geological strata and new sensitive chemical techniques are examples.

Many scientists would prefer to call this story of life changing on earth a fact, not a theory. That the changes occurred is as well-documented as anything can be in this
uncertain world. The theory comes along to explain how the changes could have occurred the way they did.

Once life successfully made the step onto land and learned to use free oxygen in the atmosphere for respiration, life also began to develop thousands of new variations. The Age of Reptiles began with small scale-covered creatures and accelerated into mammoth dinosaurs. And split off into winged creatures that one day would lead to the whole gorgeous tribe of modern birds. This was also the age of giant fernlike trees that, in dying and decaying under ancient swamps, would one day be covered by sand, compressed and altered by heat and pressure into what we today mine as coal, oil and gas.

By two hundred million years ago the first birds do appear. And only sixty-five million years ago we first see the fossil remains of furry creatures with milk glands who gave birth to live young the first mammals.

To get these enormous time scales into perspective, imagine you are making a time-lapse motion picture of the progress of life on this planet. Let each second of your movie show twenty-four years of life. On this scale 1,440 years will flash by in one minute; 86,400 years an hour; two million years a day. To show the story we are just telling, start some 730 million years ago in the ancient ocean. Your movie will then last one solid year, showing it nonstop twenty-four hours a day. Start the movie on New Years day.

The trilobites will first appear on the screen in early spring. By the end of May, fish will swim by. Not till midsummer will we see land animals and plants begin to test the free air.

In September, October and November the most spectacular actors in our movie appear—the dinosaurs. These improbable, incredible creatures dominate our screen for three months! This is called the Mesozoic era. It lasted over 260 million years. And then suddenly the dinosaurs all mysteriously disappear in early December.

The stars now become the mammals, with brains superior to anything that has come before. By the middle of December we will see monkeys, apes and other primates. But it will not be until the very last day of our year-long movie that anything resembling a human being appears.

The fossil finds of very early human beings are multiplying every year so the details of the final three million years of life history are being revised often. We know that there were quite a few human types. Neanderthal, Cro-Magnon, Pithecanthropus, Homo erectus and our own Homo sapiens.

Homo sapiens, "man the wise," did not appear until about forty thousand years ago, a mere half hour before the end of our movie. These people, our direct ancestors, slowly learned to cooperate in the hunt, in the gathering and preparation of food, in communicating in language, and finally in becoming fully conscious of their unique place in the living world.
This final conscious stage may not have happened until very recently in earth history—some scholars say not more than five or six thousand years ago, during the time of the early civilizations, two or three minutes before the end of our movie! And then in that final three minutes what a climax!

The Egyptians, the Babylonians, the Chinese, the Indians, the African civilizations rise and fall. Some brave thinkers along the shores of the Mediterranean in Ionian Greece begin to ask the first scientific questions, and give scientific answers.

One minute to go. Jesus Christ is born. Twenty seconds to go. Columbus discovers America. Seven seconds to go. The Declaration of Independence is signed in Philadelphia.

Three, two, one second—electricity, automobiles, power plants, jet planes, and space satellites zoom across the screen.

Leading to the most momentous event of our entire movie. Less than one second before the end of the movie you are born. The latest and thus far most promising experiment of life on this small planet we call earth.

That is what happened. How did it happen? How can you explain it?

1. Living creatures have more offspring than can survive.
2. These offspring have variations one from another.
3. The variations of one give it an advantage over another in a struggle for existence.
4. Those organisms with the most useful variations will survive and pass on their useful variations to their offspring.
5. Given enough time, and our movie shows how much time there has been, life will branch and branch and branch some more and some more and some more until we have what we have today.

And is that the whole story then? And do all agree? No. There is much disagreement today about evolution. And much new research actively proceeding.

The disagreements are of two sharply contrasting kinds however. Scientifically there is disagreement and uncertainty about some of the details of earth history and of the Darwinian theory, though there is broad agreement about the overall picture.

Steven Jay Gould, for example, has been the leading figure in investigating and presenting what he calls a "punctuated" theory of evolution. This is in contrast to the more traditional "gradualism" theory. He interprets the evidence in favor of sharp
changes in an evolutionary branch rather than slow continuous variations. These sharp changes could come by mutations in genetics combined with changes in the environment.

Mutations themselves—sudden changes in the molecular genes of a living organism are under much active study today. We can see evolution going on remarkably fast today in the cases of bacteria changing to become immune to our latest antibiotic. Or of insects changing their hereditary structures to escape the harmful effects of our latest insecticide. Or of some species moving to fast extinction because they could not cope with our latest environmental reconstruction.

There is also much disagreement over the role of natural selection when it comes to cultural evolution. What role, if any, has it had in racism, sexism, political and social changes? What role, if any, should it play?

Besides the churning of scientific disputes, there is today, as there was in Darwin's time, a bubbling of conflict between religious beliefs and evolutionary ideas.

Modern "scientific creationists" dispute the entire evolutionary picture presented here. In its place they have their own interpretations which place heavy reliance on ideas of geological catastrophes in the recent past, specifically the Biblical flood. The overwhelming consensus of professional biologists, geologists and paleontologists is that the Creationists are simply mistaken about this. Recent court cases have ruled that "scientific creationism" is religion, not science.

On the other hand, there is no consensus at all among scientists or nonscientists about the broader issues that often transcend science. Is there, for instance, some deeper spiritual meaning expressing itself through the evolutionary process? Does life itself have a role in the seemingly cold universe? Does God stand behind the drama of life on earth and in the universe? What is the ultimate meaning of life on earth?

This modest program cannot pretend to answer these questions. It can enter a plea for tolerance, however. Where no one can be certain, all must be free to search, to learn new meanings one from another. Make such a search yourself.

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**Scientific Methods and Values**

**Part 1: The Growth of Science**

"Wonders are many, and none is more wonderful than man. The power that crosses the white sea, making a path under surges that threaten to engulf him."
That's how Sophocles, a poet who lived in ancient Greece some 2500 years ago, described the human adventure.

Sophocles could have been giving a definition of science, as accurate then as it is now.

The two key ideas of science are here-wonder and power. Let's see how these two key ideas have grown and changed from their birth in ancient Greece to their flowering all over the world today.

The power side of science is the same power that learned how to cross the white sea; how to grow crops instead of gather them; how to herd animals instead of hunt them; how to make wheels, mold pots, extract metals and read and write languages. This power side of science came into the world long before the ancient Greeks.

It was created on this planet by people all races, all over the ancient world. It was most powerfully developed in the rich river valleys of China, India, Africa and South America. It was created and nurtured by unknown geniuses who passed on their powerful knowledge to their children and their children's children.

Today we call this power technology. Today every mechanic, engineer, inventor, craftsperson and scientist stands on the shoulders of these early human pioneers.

There is another side to modern science. The wonder side. The same wonder you hear in the small child's questions. "Why is the sky blue?" "What are stars made of?" "How did the world begin?" "Where did I come from?"

People from very ancient times also asked these questions. Some of the first people who both asked them, and then dared to answer them in a scientific way lived in ancient Ionian Greece some 2500 years ago.

The man generally considered to be the world's first natural philosopher/scientist was a Greek named Thales. The question that most fascinated Thales was "What is the world made of?"

His answer, water. The world, as he pictured it, was like a large island that floated in a cosmic sea of water. The water forms itself into soil and into plants and animals, and then all these dissolve themselves back into the cosmic ocean in eternal comings and goings.

Today what used to be the Ionian Greek city of Miletus, where Thales lived, is just a ruin of stones in western Turkey, on the shores of the Mediterranean Sea. But 2500 years ago, Miletus was the center of an exciting new idea in the world, the idea we today call science.

Thales, and the other natural philosophers of Greece, not only asked big questions like "what is the world made of?" but they answered these questions in natural terms. That is,
they left out the gods. The world, said Democritus, has no beginning, nor will it have an end. The world is made of atoms in the void.

Human beings, like other living creatures, evolved on this earth from simpler creatures in the water, said Anaximander.

Diseases have natural causes, and therefore must have natural cures, claimed Hippocrates.

Most of the answers given by the Ionian Greeks were pure speculation. They did few, if any, experiments. They had the wonder, in other words, but not yet the power. But this new confidence in natural reason laid important stones in the foundation of the sciences to come. A foundation upon which later humans like Galileo, Newton, Darwin, Curie, Einstein and Bohr would build the edifice of modern science.

After the Ionians, later Greek, Egyptian and Roman thinkers like Plato, Aristotle, Archimedes, Ptolemy and Galen added to, and multiplied, the range and power of rational thought. But for the next giant step forward, the human race had to wait almost two thousand years. This step came during what is known as the Renaissance.

Western civilization itself went into decline after the fall of the Roman Empire. For many hundreds of years it was the Arab and Moslem world that preserved and added to the beginnings made in Greece.

When we think of the Middle Ages today, we think of lords and ladies, of castles and cathedrals, of knights and monks. Scholars in the history of science point out that the Middle Ages was also of a time of much progress in science.

It was during the Middle Ages, for instance, that humans learned new ways to harness the power of nature for human purposes. New technologies were invented that used the power of the wind and water to grind corn, pump water and saw wood. Harnesses for horses were invented that more effectively used animal power. Then came new ways to improve agriculture, navigation and then in a rush, the printing press, compass and telescope as the Middle Ages merged into the Renaissance.

During the Medieval days, too, the wonder side of science was slowly gaining vision. The ancient books of Greek scientists like Aristotle, Archimedes and Ptolemy were rediscovered, translated and added to. A new interest was slowly growing in reason, in the ability of human beings to decipher the mysteries of nature, as well as the mysteries of God.

Here in the great cathedral in Pisa, Italy, a young university professor used to sit and watch an altar lamp swing slowly back and forth. Back and forth. Curious, he timed its swing with the only watch available then, his own pulse. He found it always seemed to take the same amount of time for one swing- no matter how wide or narrow the swing. He had discovered the principle of the pendulum clock. More important, Galileo Galilei
had taken a first step toward uniting power and wonder, launching modern science on its incredible voyage of discovery.

In the course of a long and adventure-filled life, Galileo helped to lay the scientific and mathematical foundations for a new way of looking at motion. A way that not only explained how things fall to the ground, but also how the moon revolves around the earth and how the earth and all the other planets move in orbits around the sun.

Galileo didn't do this alone, of course. Other giants of his day, men like Copernicus, Kepler and Tycho Brahe played important parts in creating modern science. Probably the most important single man of all was born the same year Galileo died. He was born and lived in England. His name was Isaac Newton.

A famous English poet of the day, Alexander Pope, expressed the general opinion of the time about Newton's achievements.

"Nature and Nature's laws lay hid in night: God said, Let Newton be! and all was light."

During these heady days, for the first time in human history, the heavy thinkers and the heavy doers were edging closer together. It was no longer good enough to just ask big questions and give purely speculative answers. The answers had to have practical consequences, consequences you could see, feel, touch, taste and measure.

When you did thus test your theories in practice, you often were surprised. Thinking about the surprise, you could go back and change your answers, making them more truly fitting with reality. The idea we call experimental science was beginning to take shape.

In the next few centuries, progress in understanding and in controlling natural events with the aid of experimental science began to gain momentum. Sometimes the wonder side of science led the way, especially in astronomy and natural history. And sometimes the power or technology side of science led the way, as in the fast pace of invention in the nineteenth century.

The nineteenth century in Europe and North America was the century of the Industrial Revolution. The Industrial Revolution combined the power of science and technology with the equally powerful ideas of democracy, capitalism and free trade. Out of this creative mix came inventions like the steam engine, electrical generators and motors, wireless communication, internal combustion engines, as well as a host of new scientific tools.

Though it came later, progress was also made in the life sciences and in medicine. Instead of basing cures to human ills on folk medicine, astrology or other fanciful theories, humans slowly began to rely more on the scientific discoveries of biologists, chemists and physicians. Why? Because they worked better.
In the late nineteenth century and then most dramatically in our own twentieth century, most of the terrible epidemic diseases were conquered. Some have called this the "noblest chapter in human history." And with good reason. Diphtheria, typhoid, smallpox, cholera, syphilis, tuberculosis, polio and plague all gave way before the onslaught of power and wonder people. And that conquest continues today in countries around the world.

In our time, the influence of scientific method and of scientific values has spread into the social and political worlds as well. As yet, it has not proved as useful there as in the physical and life sciences, but few would doubt the potential for the future.

In such a fast survey of the growth of scientific methods and values, there is a danger we think of famous scientists as being godlike. Or imagine they all use a magical tool called scientific method, and through its use, perform miracles. Some people think of scientists as men and women in white coats, hunched over their test tubes and machines, working all hours of the night, risking their own and other people's lives in an almost demonic desire to know.

When you read of the lives of individual scientists, you quickly see it wasn't that way. You see, instead, how scientists in their personal lives have been just about as varied a group an any other that has lived on this planet.

John Dalton, for instance, was a retiring modest bachelor. Poor, colorblind, he taught in a small Quaker elementary school in England. He never married. "I just never had time," he claimed. He was rather clumsy in the science laboratory. Yet despite these traits, or perhaps because of them, he managed to invent a theory of atoms that brought a revolution to the new world of science.

Galileo, on the other hand, was as aggressive and social as Dalton was retiring and solitary. Galileo never married either, but he lived with a mistress for many years. He loved wine. He loved a good argument. In fact, he was continually getting into hot water with the authorities not only because of his unorthodox opinions, but also because he was so abrasive in putting them forward. And yet despite these traits, or perhaps because of them, he managed to overturn centuries of error and to father modern physics and astronomy (as well as five children with his unwed mistress). And throughout it all, to remain a devout Catholic.

If we had world enough and time, it would be easy to multiply these two examples a hundredfold. A thousandfold.

There were grumpy geniuses like Charles Babbage, who designed the world's first true computer. And charming young geniuses like Ada Lovelace, who helped him design it and went on to herself become the world's first computer programmer. As well as to lose most of her money trying to use the computer to pick the winners of horse races!

There have been wealthy, irascible woman haters like Henry Cavendish who discovered hydrogen, the composition of water and weighed the earth.
There have been devoted family men like Charles Darwin who shocked and changed the world with a theory of evolution by natural selection.

There have been poor young women like Marie Curie, who discovered radium, pioneered the way for women in science, and was the first person ever to win two Nobel prizes. In between all these scientific achievements, she also managed to have a happy marriage and two daughters who became famous in their own right as writers and scientists.

There have been, and are, devoutly religious scientists. There have been, and are, devout agnostic and atheist scientists. Family men and women, gay men and women, black men and women, young and old men and women.

Handicapped and not, social and not, athletic and not, clever in the laboratory, and clumsy with their hands.

In other words, there is no typical scientist, just as there is no typical business person, teacher, artist or truck driver.

But there is such a thing as science. And there are such things as scientific methods and scientific values. Methods and values that all the major and minor figures in science, yesterday and today, have followed and lived by.

**Part 2: The Methods and Values of Science**

"The mysterious," said Albert Einstein, "is the source of all true art and science."

"Science," said Thomas Edison, "is one percent inspiration and ninety-nine percent perspiration."

"A mouse," said Walt Whitman, is miracle enough to stagger sextillion of infidels."

Each of these three ingredients—the mystery, the work and the surprise—is indeed a part of modern science. And there are others.

When people write or talk about scientific method, they often write or talk as if it were a single thing. Most scientists would disagree.

The truth is, most scientists don't particularly like to talk about their methods at all. They much prefer to tell you about their problems and their results. And usually with heavy use of phrases like "it seems," "the probability is," "within the limits of our experiments."

In other words, besides mystery, work and surprise, scientists also prize caution, limits, not going beyond the evidence, taking care that whatever statement is made, it should be verifiable in practice. Wonder, speculation mystery are fine, so long as they have a firm connection to power, hard data, fact.
A Nobel laureate, Sir Peter Medawar, put it this way. "Most of the day-to-day business of science consists in trying to find out if your imagined world is anything like the real one. If it is not, we have to think again."

So there you have it—the two sides—the two tricks to both scientific methods and scientific values. Imagination and reality. Mystery and fact. Wonder and power.

On the one side, scientific methods and scientific values are on the side of wild fantasy. On the side of the most outrageous, passionate, imaginative search you can imagine. A search for a new world of truth and light. A way of penetrating the mysteries of the cosmos. The mysteries of the human mind and body. The mysteries of an ant hill, a new gear system or a new molecule.

On the other side scientific methods and values are on the side of sober caution. On the side of sticking to the facts. Of care, nitpicking attention to detail, scrupulous concern for absolute honesty.

Once you get the imagined world and the real world into a working relationship, you have science. You have knowledge. Knowledge that works. Knowledge that can send off some of the brightest sparks of joy and delight humans seem capable of seeing.

Many humans who are not professional scientists experienced some of that joy that works when they saw the first blue-white photos of our spaceship earth.

Think how much imagination and care went into getting those first photographs from space and you will have a better idea of what scientific methods and values are all about. Not only the imagination and care of the engineers, scientists, mechanics and astronauts today, but all the engineers, scientists, mechanics and pioneers whose work came before. The people who first invented cameras, who perfected film. The people who first built and flew airplanes, designed and tested the first rockets. The people who learned to make better steel, plastics, aluminum and ceramics. The people who dreamed up computers and computer programs. The pioneers who had the courage and skill and perseverance to never give up, to-try again after a failure, to take still another chance—and to succeed.

Each scientific worker has been able, in other words, to build on the work of those who have gone before. Preparing the way. As one of the greatest scientists, Isaac Newton, put it, "If I have seen further than other men, it is because I have been able to stand on the shoulders of giants."

Each scientific worker has been subject to a harsh standard. Does it work? Does it predict correctly? Does your fantasy world fit with your reality world? And not for you alone, or for you and a few like-minded friends—does it work for the public, for everyone in all times and all places? Only so can it be called science. Only so can it be called true.

Not every enterprise that has claimed the title of science can pass these stern tests. Astrology, for instance, is also an attempt to connect a fantasy world with a reality world.
There have even been some famous scientists, like Johannes Kepler, who have been astrologers as well.

Over the long pull, however, astrology fails the most crucial of all scientific tests. It doesn't work. Publicly. At all times and all places. Mind you, astrology does work sometimes. The imagined world of a personal horoscope sometimes may even may predict with astonishing accuracy a person's traits or a person's future actions. But when faced with a critical, public test, astrology always flunks. And astrology has flunked over and over again for centuries. One result of this failure is that knowledge of astrology today gives no more power to individuals or to society than knowledge of astrology did a thousand years ago.

On the other hand, knowledge of astronomy, or physics, or chemistry, or biology, or ecology or geology- gives power a thousandfold as great today as it did a thousand years ago. Or even ten years ago!

The same contrasts stand out when you compare genuine science with other occult practices of the past and present. Psychic surgery, astral projection, spoonbending, miracle cures, Bermuda triangles, etc. All these can point to remarkable instances where the world of fantasy did indeed seem to connect with our world of reality. But none of these occult practices can pass the harsh scientific test of public verification over the long stretch. And as a result, none of them has led to any real increase in human power or wisdom. In other words, not one of them works-not publicly, consistently, reliably.

Instead of being able to see farther by standing on the shoulders of those who have gone before, with the occult, at best, you can feel better by holding hands with those who believe as you do. And as the horizon fades, the sight dims.

Let's be more specific now. Granted that science tries to connect an imagined world with the real world-what hints do we get from successful connections of the past as to just how it can be done most fruitfully today.

There is no recipe.

Many textbooks claim that scientific method means starting with a problem. You construct a hypothesis to solve the problem. Then you test to see if your hypothesis is true.

Most of the time, the hypothesis turns out to be false. But then, that in itself is knowledge. Verifiable, scientific knowledge. As Thomas Edison once said, "I may not know how to make a light bulb yet, but I do know 10,000 ways that won't work."

This way of looking at scientific method is true enough, as far as it goes. But it doesn't go nearly far enough. In the real world scientific laboratory, in the real world scientific study, in the real world, it gets more complicated. And more interesting.
For one thing, no seed can grow unless you prepare the soil. In order to find out something new you need to know many things old. You are not likely to discover a cure for cancer if you don't know anything about cells, about genetics, about biochemistry, perhaps even about poetry and anthropology. There is no formula, but experience has shown that the more intensely you become preoccupied with a problem, the more sides you see to the problem, the greater your chances of solving it. With the emphasis on intensity.

Often what it takes is a near total immersion in the problem, the challenge, the quest. Which is why scientists often are looked on as absentminded. It is not that their mind is "absent" but rather that it is so intensely concentrated on the challenge that they don't pay attention to anything else at the time.

Of course experience has also shown -note the scientific caution again- that it is possible to know too much about a subject. To know so much that your mind is not as free to imagine new connections. Connections that may show some of what you know is not true, or is only a dangerous and misleading half-truth. This is one reason some of the best scientific work is often done by quite young men and women. They don't know so much that isn't true.

Again, there is no magical recipe. Study in, around and about a subject. Study intensely, deeply, widely-but don't believe everything you read! Besides the study of past knowledge in the field, the scientist would usually want to get his or her hands involved. Or at least to think ideas that someone else could in fact test out with fingers and eyes and noses and ears-and if possible, measurements in numbers.

Sometimes, more often than not, it works the other way around, too. The scientist, or technician, or engineer, or craftsperson comes across a new idea in the process of constructing something. Or experimenting with something. Or just plain fooling around with something.

One recent historian of science pointed out that the unsung heroes of the famous Cavendish Laboratory at Cambridge University were the technicians who used sealing wax and string to patch together the custom-made research equipment. And in the process helped piece together the pieces of modern atomic theory. All, incidentally, with a yearly budget for research equipment of less than a thousand dollars a year in 1908.

Since there is this intimate connection between wonder and power that runs through all the best of science, it is not surprising that there is such an intimate connection between technology and theory. Between the workshop, the laboratory and the study. Different scientists are more at home in one than another, but all are aware of how important each of the places and pieces is.

We have talked of scientific methods. What about scientific values? There is a close connection between methods and values in science. Sometimes it is hard to tell which is which. You can look at scientific values much as you look at scientific methods.
On the one hand, caution, limits and care. On the other hand, imagination, wonder and passion. The methods of science are there, and so are the values. Both in the passion of the search and in the purity of the limitations. Wonder and power, hope and caution, mystery and fact, paradoxes that work.

On the side of limitation, you might think of scientific values in terms of the famous Murphy's Laws. "If anything can go wrong, it will." In other words science is not satisfied with easy answers that work once but are not reliable over the long pull. Once you really know something, it will work time and time again.

Just because it is in the newspapers doesn't mean it is so. In other words, science is perpetually the skeptic. Show me. Prove it to me. Prove it to me not in words, but in deeds. In experiments.

Honesty is the best policy—but cash on the line is even better. In other words, results count. And the worst sin a scientist can commit is to falsify his or her results. To lie. Science does have an advantage here. The cheater, the liar, and there have been some in science, is almost certain to be found out. Because part of the very core of scientific truth is that it can and must be verified publicly, independently. It is, thus, self-correcting.

"The spirit of liberty is the spirit that is not quite sure it is right." This is a "law" made by a famous judge, Learned Hand. He could have been talking about science as well as of democracy. And, as a matter of fact, science at its core is a profoundly democratic enterprise. The passion of a free people, who have faith, but a faith that can stand challenge. A faith that can change as new knowledge comes along.

On the passion side of science, we might coin some new laws. Let's call them Riley's Laws (Murphy's optimistic cousin).

"The mysterious is the source of all true art and science." Albert Einstein said that. He also said "imagination is more important than knowledge."

"It is not the immensity of space that should command our wonder, but rather the man who measured it."

"Dare to be naive." Advice given by a modern scientist and engineer, Buckminster Fuller.

"There is a vitality, an energy, a quickening, which is translated through you into action. And because there is only one of you in all time, this expression is unique. And if you block it, it will never exist through any other medium and be lost. The world will not have it." Said by a dancer, Martha Graham, but she could have been talking about one of the most precious values of science as well. The conviction that in the long run, human beings play a part, human beings have a voice and a vote in the universe.

Which brings us back to the beginning. To that fabled time in ancient Greece, 2500 years ago, when Sophocles put it into words:
"Wonders are many,  
and none is more wonderful than man,  
the power that crosses the white sea,  
making paths under surges  
that threaten to engulf him."