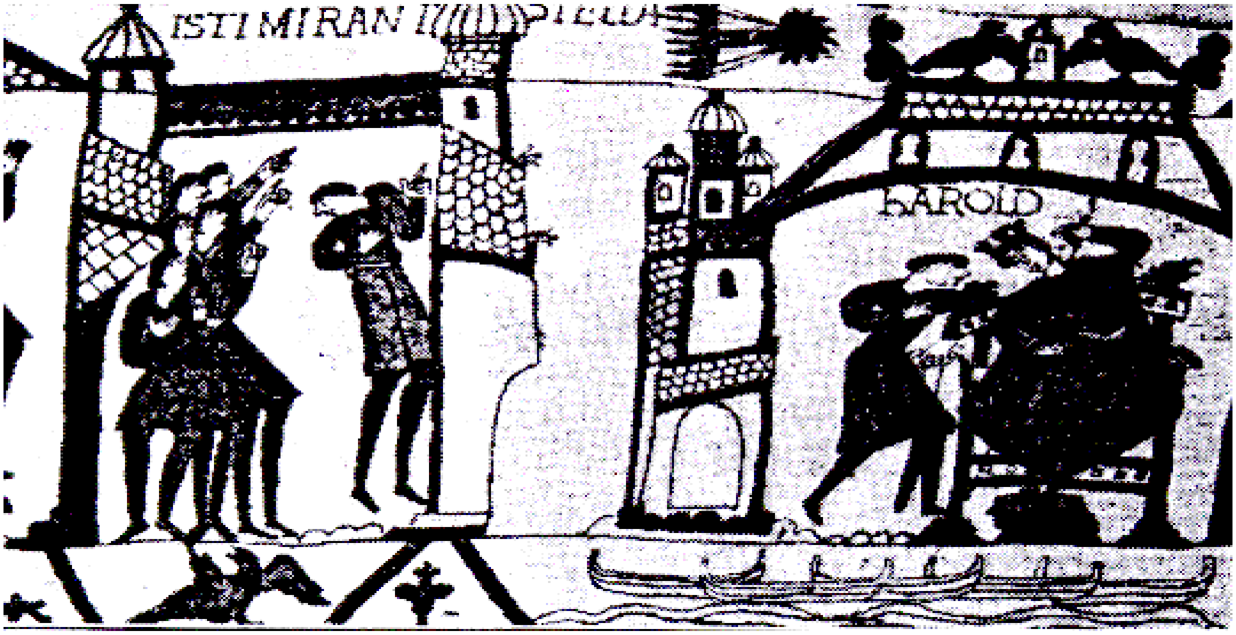


Detail from Bayeux Tapestry, which chronicles the Norman conquest of England. This section of the large tapestry illustrates people 's reaction to the appearance (if Halley's comet in 1066. The comet was widely said to predict defeat for the English by William the Conqueror. Today, no educated person needs to believe that comets, planets, or stars can affect human affairs.

Getting To Know Us

by Gordon Kane

Since at least the dawn of history, human beings have been interested in their own origins and in the make-up of their world. Most cultures, for example, have "origins" stories in their religions and myths to explain what and who we are. But until what we call "science" gained a foothold, no explanation provided verifiable conclusions. Only with the advent of the scientific method and the ever-increasing knowledge gained through this method-came confidence that the universe and everything in it operates according to understandable laws, confidence, as well, that many questions once thought beyond human ken are answerable, perhaps even in our lifetimes. The word "science" derives from the Latin *scientia:* "knowledge." Specifically, it means knowledge about the natural world, of which we are all a part; yet, to a large degree, science is regarded as an isolated activity practiced by pale individuals boxed up in dull buildings. In fact, science is both a product and a determiner of culture. But although by now nearly all cultures have been affected by science, not all cultures produce science. Let's look at why science has flourished in some cultures and, in turn,

The word "science" is used and misused in a number of ways. Whenever words are used in inconsistent ways, they lose their meanings, and "science" is too important a word to lose, so we should not let it mean more or less than this definition: science is the attempt to understand the natural world by making an informed guess about some aspect of interest; testing, or probing, the consequences of that guess by observation and experiment; and revising the guess until guess and observation agree with each other and with all earlier scientific results. "Science" includes, therefore, not only the method, but also the accumulated knowledge of all successfully tested guesses.

Science and technology

Science is often confused with technology. Science is about understanding the world; technology is about changing it. Technology is the development of new devices that affect our lives, and technology exists in all cultures. Arrowheads, fire pits, the alphabet, gunpowder, and penicillin are all products of technology. Until about a century ago, science and technology mainly developed independently, though there was some overlap, and technology often preceded science. Glass lenses, for example, a technology originally intended for eyeglasses. led to the development of telescopes that scientists could use to study the heavens and to microscopes that make it possible for scientists to probe previously invisible distances.

Nowadays, the table is often turned, and science leads to new technologies by two routes. First, new understanding of the world often leads to invention of new devices. Second, in order to probe new frontiers of nature, scientists often have to invent new devices for observation, experimentation, and measurement-the World Wide Web, developed by physicists for their own quick information and data exchange, is a recent example. Until scientific understanding of electromagnetic waves led to the invention of communication devices, including radio and television, almost all technology arose through tinkering rather than through the application of scientific understanding. TV, computers, and other complex technologies created

A brief history

Once upon a time (up till about 2600 years ago, as it happens) there was no science in the world. Where did it come from? How did we get from none to lots? Why did some cultures learn to do science, while others did not? It's possible to examine the answers to these questions and thereby to better understand not only science, but culture as well.

Surely many people in many cultures have wanted to understand the natural world, which included themselves, but there were no rules handed down about how to satisfy their curiosity. People had to invent a method that worked, along with learning the results. Some cultures, it seems, proved more congenial to science than others. For science to progress, a culture requires four characteristics: It has to encourage the idea that the world obeys causal natural laws; it has to believe that humans can discover and understand those laws; it has to tolerate new ideas that are often inconsistent with accepted wisdom; and it has to have the wherewithal and commitment to support the people who study the new ideas.

A scientist can get just as much acclaim for showing that a purported result is incorrect as for confirming it, so all important work is carefully scrutinized by competitive colleagues.

Although technologies can be traced further back and through many countries, our scientific history began in what is called Ionian Greece, a scattering of city states on islands and along the western coast of present-day Turkey, about 600 13CE. From that beginning to modern science, we can trace an unbroken, though jagged, path.

Because Greece was emerging from a period of cultural decline that followed the great Mycenaean and Cretan cultures, traditions there were not as strong as they were, for example, in China at that time. Also, the Ionian city-states had become trade centers at the crossroads of several cultures: Persian, Egyptian, Middle Eastern, Macedonian, Scythian, Mediterranean, and more' With numerous nearby city-states, no single government could enforce intellectual conformity-and this may have been critical in the development of science. Science challenges standard explanations, and the challenges often make its practitioners unpopular, but an Ionian could, if his ideas were considered threatening in one city-state, simply move and continue "research" in another.

Prosperity, mainly generated by trade, led to a class of merchants who wanted their children to be well-educated and who could afford to support teachers, intellectuals who had time to think about the world. The trade-based economy created a class of people who were worldly in outlook, with knowledge of the languages and cultures of others, with flexibility about customs, and with open minds receptive to new ideas.

The alphabet, which arrived in Ionia via Phoenician traders, brought immense benefits. The peak of Ionian Greek culture followed the emergence of alphabetic writing affords enormous power and freedom in formulating and expressing ideas. Its predecessor, hieroglyphic writing, based on analogies between characters and objects, did not encourage abstract thought to flourish, and because of its cumbersome nature, it remained the monopoly of a priestly or bureaucratic caste. The alphabet and consequent widespread literacy broke through old borders of thought and facilitated the development of abstract logic, which in turn was essential to the growth of science.

Another important factor was Greek religion: Greek gods were not inimical to human ideas about creation and the workings of the universe. They were a lusty, bargain-driving, rather human bunch, and the pantheon of gods even included a goddess of knowledge.

The combined freedoms of thought allowed the Ionian Greeks to ask many questions about the natural world that we too ask or have already answered. Their answers are now mainly of historical interest, but their methods of thought started us on the path to the modern era. The book by the Roman Lucretius, On *the Nature of Things*, is a wonderful summary of the best of the Greek thinking; in many ways it gives a modern view of the goal of understanding the world.

After the Persians conquered Ionian Greece, Greek science faltered. In Athens it survived but did not flourish. Aristotle did interesting science-though his results were almost always wrong (he argued, for example, that matter was not made of atoms, and that a vacuum is impossible). In the new and cosmopolitan Alexandria, science again flourished after 300 BCE, until the famous library there was burned by Christians about 400 CE, at the beginning of the medieval dark ages. Until conditions were again ripe for science in Europe, as the Renaissance began, much of Greek science survived and was enriched mainly in the Arab world.

By the 14th century, the city-states of Italy and southern Europe were in many ways like those of Ionian Greece, and many of the same intellectual conditions held. After the middle of the 15th century, the success of the printing press guaranteed that science books would get wide distribution, and helped ensure that science would not only survive but grow and thrive in the western world. Recognizably modern science began as the 16th century ended, with Brahe and Kepler and Galileo and Harvey and others.

Democratic science, where anyone can work on any research question, is quite simply the best method to get general, correct results about the natural world from normal, fallible people.

Before we go any further …

Three barriers often stand between the public and a loving reception of science. The first is that much science depends upon difficult mathematics or on knowledge of previous scientific results. Although, in theory, everyone is capable of learning this math and the previous results, relatively few do, and consequently the public has to trust scientists about the validity of results and has to rely on the often awkward verbal explanations of scientists. An inadequate understanding of scientific explanations leads to the next two barriers: 1) hostility, because of occasional media revelations of scientific cheating or errors, and 2) confusion, following media reports of scientific breakthroughs that seem to contradict earlier scientific information.

In response to these "charges," it is important to note that in the physical sciences (physics, astronomy, chemistry), there are essentially no documented cases of successful interesting fraud, i.e., fraudulent claims about important results, despite hundreds of thousands of publications. That is because experiments and calculations can be repeated by other scientists --- and they will be, if the problem is interesting. A scientist can get just as much acclaim for showing that a purported result is incorrect as for confirming it, so all important work is carefully scrutinized by competitive colleagues. Of course, incorrect results are occasionally reported, but competitive checks within the scientific community will soon find them out.

In the biological and social sciences, it is much harder to repeat procedures, because it is much harder to isolate systems, and fraud is attempted occasionally. Nevertheless, it is still caught, almost always fairly quickly. Democratic science, where anyone can work on any research question, is quite simply the best method to get general, correct results about the natural world from normal, fallible people.

As for revisions of previous conclusions, during the time when any scientific sub-field is developing, its "results" should change, and they do. As ideas are tested, some conclusions are verified, and the sub-field moves ahead. Eventually a full understanding of that sub-field emerges, and after that, its results are unlikely to

Extending knowledge

Sometimes answers to scientific questions come quickly; sometimes not. An extreme case of "not" was the idea of atoms. The Ionian Greeks actually asked whether matter was composed of pieces that could not be further broken down or was continuous, but because atoms are too small to detect with the naked eye, no progress was made on this question for about 2,300 years-although during that time there were lots of unconvincing philosophical arguments.

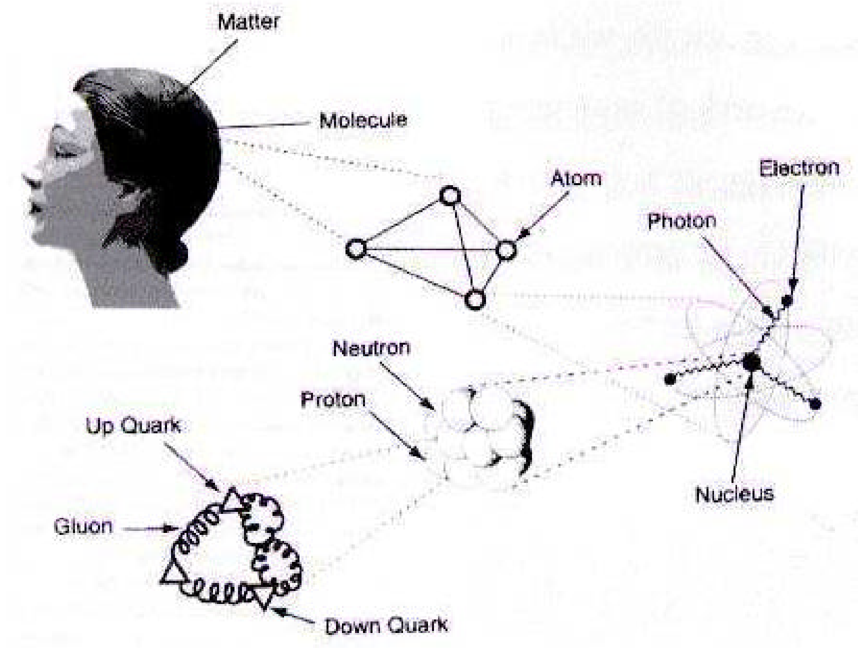
Indirect arguments from chemistry and thermodynamics strengthened the case for atoms, and the matter was finally settled only in the early years of this century. Still, though scientists agreed that atoms existed, no one knew what they were. Then, in 1911, Ernest Rutherford showed experimentally that atoms are composed of electrons bound to a tiny nucleus. Fifteen years later, quantum theory was formulated, leading to full understanding of atoms and the chemical elements.

But the atoms of chemistry turned out not to be the Greek "atoms," the smallest constituents of matter. The atoms of the chemical elements themselves had structure and were made up of smaller parts. They had nuclei, which in turn were made of protons and neutrons, and were fenced by orbiting electrons. Finally today, after the invention of accelerators and some decades of experiments, we have good evidence that everything we see in. the universe --- everything on earth, including ourselves, and the stars-is made of just three structureless (non-divisible) sub-atomic objects: electrons and two similar particles called "quarks."

Starting from electrons and the two quarks, we can understand the structure of protons and neutrons, then nuclei, then atoms, then molecules, macromolecules, cells, organisms, animals, mountains, planets, stars, and galaxies. Electrons and the two kinds of quarks are the basic constituents of all visible matter. (There are additional particles, but they occur only in collisions of cosmic rays in the atmosphere, or, if created in accelerators; they exist for only fractions of a second, and do not contribute significantly to the matter that makes either stars or us. There may also be particles that make up a large amount of "dark" matter in the universe, matter we detect because of its gravitational attraction but otherwise do not see; this is a subject of current research.)

A universe that behaves in understandable ways, though, requires not just matter, but also forces that determine how matter interacts, and rules by which those forces operate. The rules have been known since 1925. They are Einstein's special relativity and the quantum theory. Their applicability has been tested over a huge variety of situations, and there is little doubt they will remain the correct procedures to calculate what happens in our universe.

The first clear formulation of the idea of "force" came over 300 years ago, when Newton described how gravity and motion work. It had taken more than 2,000 years of fumbling at the lock until Newton's insights, the first major achievements of the scientific method, provided the key that opened the gate to vast expansion of scientific knowledge. As his results passed test after test and led to the successful explanation of the age-old problem of the tides, to the successful prediction of the return of Halley's comet (removing comets and other heavenly bodies from the realm of superstition), to the successfully predicted discovery of the planet Neptune, to demonstrating that motion on the earth and in the "heavens" is governed by the same laws, and much more, people naturally became excited and enthusiastic



*All **matter is made of molecules, which** are combinations of atoms. Each **atom has** a nucleus with electrons bound to the nucleus by photons. Protons and **neutrons** are made of quarks bound by gluons. A typical small molecule has a diameter of about one-millionth of a centimeter a typical atom about a tenth of that. The diameter of a nucleus is about 1/10,000th of its atom. A proton or a neutron is a few times smaller than a nucleus. Quarks and gluons (and electrons and photons) do not have any structure, as far as we know today.*

about the power of scientific thinking and about Newton's results, in particular. The laws he described seemed to hold universally.

But, early in this century, over 200 years after Newton formulated his results, we learned that the laws Newton described were not fully universal. For objects the size of atoms or smaller, or for objects moving faster than thousands of miles each second, Newton's laws turned out to be inadequate. Some people, drawing a wrong conclusion from this limitation, argued, incorrectly, that no law of nature is ever totally valid, and that descriptions of nature would continue to change forever.

In fact, nothing at all is "wrong" with Newton's laws; they are accurate for the world at the scale of our senses. At larger and smaller scales, however, they needed to be extended. What we learned is that theories of science must be specified in terms of variables, such as speed or size or distance. Tests apply over some range of those variables, and if the original guess is expanded to cover a larger range, new tests may be required. This is not invariably the case: some laws do not need to be extended at all: for example, the first and second laws of thermodynamics, i.e., conservation of energy and increase of entropy.

By the beginning of the I 91h century, we knew that three forces regulate our world-gravitational, electrical, and magnetic. Then, early in the 20th century, it became clear that two more forces operate at the level of sub-atomic particles-the weak force and the strong force, which have no effects at all outside of atoms, though without the strong force, nuclei would fall apart. Today we have a successful theory (called the Standard Model of particle physics) that describes all the forces and their effects on quarks, electrons, nuclei, atoms, molecules, people, stars, etc. Any further extension of the theory will apply only at distances much smaller than the size of a proton and will not change our understanding of the workings of the world at our scale. Scientists still hope to increase our understanding of the successful theory of the forces. Perhaps we will eventually be able to understand the five forces as different facets of one encompassing conceptual unification, but such a development would not change the practical success that has been achieved in describing how nature works.

Knowledge and freedom

As science progresses, society is affected in many ways. Scientific knowledge has not only made possible obvious technological advances, ranging from communication technologies to medical procedures that save lives; it may also provide understanding that gives us advance warning of possible problems, such as global warming. But perhaps more importantly, if the laws of nature can explain what we observe and help us understand the universe, then the universe comes to seem a more stable place. Such knowledge can free us from superstition, ignorance, and false information.

There have always been two ways to know that belief in phenomena such as astrology and extrasensory perception, for example, are superstitions rather than reality. First, the predictions *obviously* do not work out. They never tell us anything interesting or significant (if they did, election ballots would be unnecessary and lotteries would be dull), and if they turn out to be accurate, they fit within the realm of probabilities, like guesses or the outcome of the flipping of a coin. Second, claims about astrology and ESP and such phenomena can be studied systematically in controlled experiments, and that has been done repeatedly and conclusively, to their detriment. But now, we have enough knowledge to invalidate such beliefs without testing each and every one: we can prove that they are simply inconsistent with the laws of nature.

We can now say with confidence that anything that happens does so via the five forces of nature. Because we and everything in the universe are all made of the same atoms, anything that can affect us can also affect detectors made of the same atoms. If unknown signals or influences could affect our brains or bodies (which are made of the 92 chemical elements), they could be detected with equipment made of the same 92 chemical elements. In fact, for all the forces, we now have laboratory detectors that are considerably more sensitive than our brains and bodies. Furthermore, knowledge of the conservation of energy allows us to calculate that our bodies cannot supply enough energy to send electromagnetic or gravitational signals to other bodies. The weak and strong forces are too short-range for a signal to appear outside a nucleus. Thus ESP and astrological effects are inconsistent with the laws of nature.

Before the mid 1950s, we did not know enough about the forces of nature to make these arguments, and even as recently as two decades ago, we could not be sure of them, but now our understanding of the laws of nature provides constraints on all claims about the world. Of course, someone could say that there are "unknown effects" that can somehow violate energy conservation but cannot be detected by normal laboratory equipment and tests of energy conservation, or can affect, say, potassium atoms in our brains but not identical potassium atoms in detectors in the laboratory, and that these effects not only exist but somehow can give rise to coherent thoughts in us. Those who might say such things should understand that what they are invoking is not consistent with nature operating according to natural laws.

Surprisingly, and perhaps more obliquely, there is evidence that advances in physics influenced political thinking. The idea of universal natural laws, issuing from Newton's work, influenced the thinking of John Locke, Voltaire, and others, who in turn affected thinking about political systems. Newton's demonstration that a stable system could exist by balancing opposing forces was explicitly credited with helping lead to the to ' rm of government we now have, with balanced executive, congressional, and judicial forces. The Newtonian view of a universe running smoothly, subject to a few general rules, helped convince people that the American and French revolutions were justified. It helped give the American Revolution its positive aspects --- it was not just a rebellion, but an attempt to create a new kind of government and a new kind of society. *(Science and the Founding Fathers* by 1. Bernard Cohen discusses these fascinating topics at length.) Even the goal of universal human rights was not institutionalized before the idea of universal applicability of the laws of nature; laws relating to human rights were, until relatively recently, applicable only for members of a tribe, not for outsiders.

More widely recognized is the contribution of communication satellites, a science based technology, to increased personal and political freedom in the late 20' century. Once people in totalitarian countries learned through radio and television that people in democratic societies enjoyed more freedom and better health and economic conditions, it became much harder to keep them under dictatorships. As the Iron Curtain fell, people also made powerful use of communications systems to appeal to the rest of the world for help. It is not an accident that in countries where people protest government restrictions, the signs at demonstrations are half in English-to be read by the world-wide TV audience.

If the laws of nature can explain what we observe and help us understand the universe, then the universe comes to seem a more stable place. Such knowledge can free us from superstition, ignorance, and false information.

Looking forward

Our understanding of the laws of nature now extends back nearly to the beginning of the universe, out to the edges of the visible universe, and inward to distances much smaller than atoms. Although what we know can never be "proved," because, in principle, new data could contradict any law at any time, new results are not likely to lead to changes in the domain where the laws are already well tested.

Still, there is much research in progress. We have not answered all the questions that can be asked. We don't, for example, yet understand how the universe began, or why there is a universe at all, or what space and time are, or how to unify the laws into a single encompassing one. We do not yet understand human consciousness or know if there is intelligent life elsewhere in the universe. But we have come far enough now to view all of these questions, for the first time in history, as scientific research topics, rather than philosophical or religious issues.

Sometimes people who do not understand science claim that questions about the distant past, or about laws that may be unified only at distances so small we cannot do experiments there, or about our own consciousness, cannot be answered because explanations cannot be tested. That is wrong: we don't need to have been present at the Big Bang to deduce and confirm its validity through powerful experimental tests. For example, the Big Bang theory predicts that about 24 percent of the matter in the universe should be helium left over from the first three minutes of the universe, and that is observed to be correct to an accuracy of about 3 percent. It also predicts that the radiation emitted in the early universe should have cooled to a temperature today of 2.726 degrees Kelvin, a prediction confirmed to an accuracy of better than a tenth of a percent. Likewise, we can come to reasonable conclusions about much of the past, such as what happened to cause dinosaurs to become extinct. Consequences and relics of events, in other words, provide powerful evidence of the events themselves, and scientists can always rely on such information to extend knowledge.

Are there limits to what we can understand about the natural world? So far there are no significant arguments that imply so. The method of science is to aim for understanding and see what happens. Probably the largest danger is that the scientific enterprise is fragile; it is dependent on financial and cultural support, and that support isn't guaranteed, because science and its results can seem threatening to some people, while others view science with indifference. Only if our culture and our society and our universities have a sufficiently deep commitment to providing the resources and the opportunities, will we continue to increase our understanding of what's out there and in us.

Gordon Kane is professor of physics. His most recent book is The Particle Garden**:** Our Universe as Understood by Particle Physicists, (1995).