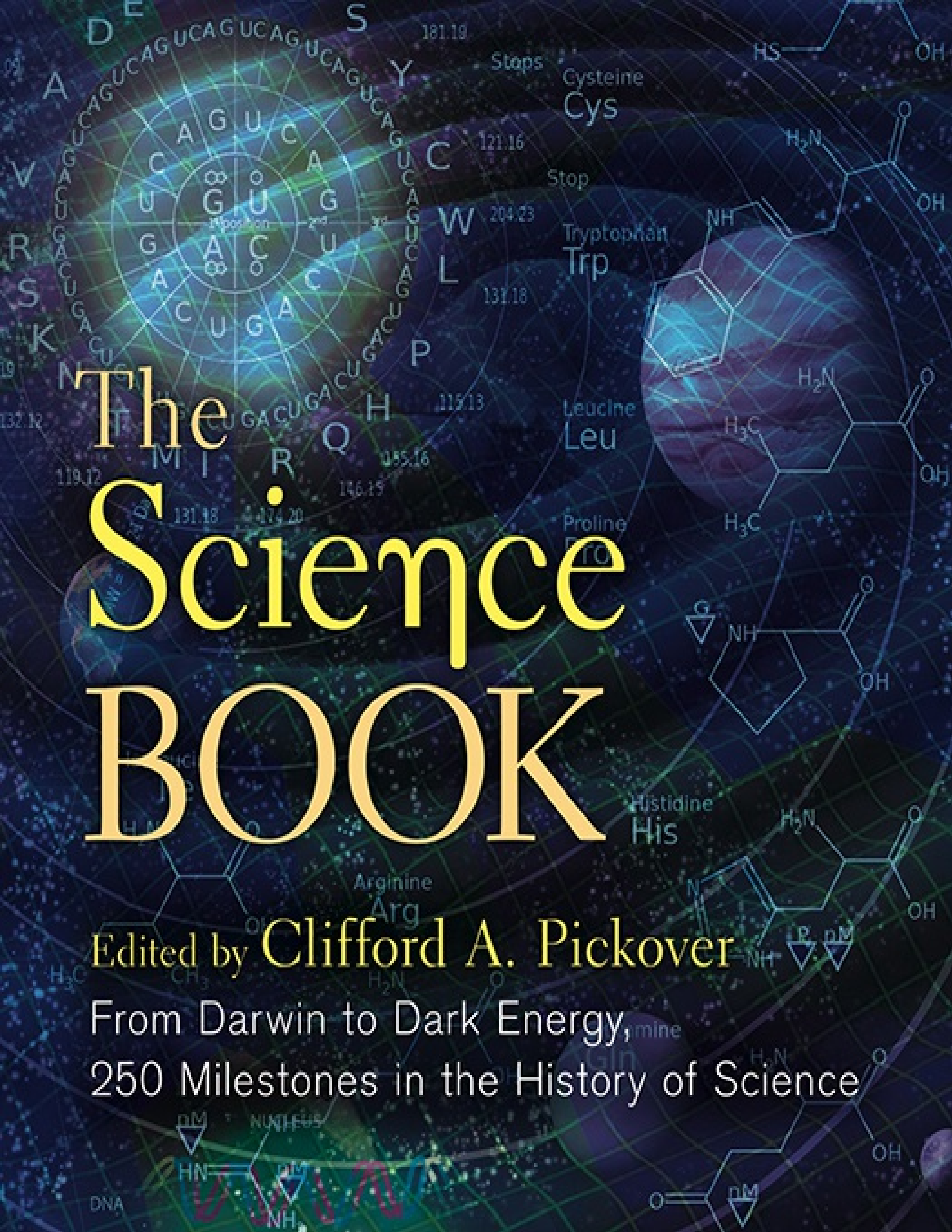


The Science BOOK

Edited by Clifford A. Pickover

From Darwin to Dark Energy, 250 Milestones in the History of Science

THE SCIENCE BOOK

From Darwin to Dark Energy, 250 Milestones in the History of Science

Clifford A. Pickover

STERLING
New York

STERLING
New York

An Imprint of Sterling Publishing Co., Inc.
1166 Avenue of the Americas
New York, NY 10036

ISBN 978-1-4549-3300-7

For information about custom editions, special sales, and premium and corporate purchases, please contact Sterling Special Sales at specialsales@sterlingpublishing.com.

sterlingpublishing.com

See page 526 for Photo Credits.

Contents

1964 Brain Lateralization Michael C. Gerald with Gloria E. Gerald
1964 Quarks Clifford A. Pickover
1965 Cosmic Microwave Background Clifford A. Pickover
1966 Dynamic RAM Marshall Brain
1967 Endosymbiont Theory Michael C. Gerald with Gloria E. Gerald
1967 Heart Transplant Clifford A. Pickover
1967 Saturn V Rocket Marshall Brain
1969 ARPANET Marshall Brain
1969 First on the Moon Jim Bell
1972 Genetic Engineering Marshall Brain
1975 Feigenbaum Constant Clifford A. Pickover
1975 Fractals Clifford A. Pickover
1977 Public-Key Cryptography Clifford A. Pickover
1978 Theory of Mind Wade E. Pickren
1979 Gravitational Lensing Jim Bell
1980 Cosmic Inflation Clifford A. Pickover
1981 Quantum Computers Clifford A. Pickover
1982 Artificial Heart Marshall Brain
1983 Epigenetics Clifford A. Pickover
1983 Polymerase Chain Reaction Clifford A. Pickover
1984 Telomerase Clifford A. Pickover
1984 Theory of Everything Clifford A. Pickover
1987 Mitochondrial Eve Michael C. Gerald with Gloria E. Gerald
1990 Domains of Life Michael C. Gerald with Gloria E. Gerald
1990 Hubble Telescope Clifford A. Pickover
1990 World Wide Web Marshall Brain
1994 Global Positioning System (GPS) Marshall Brain
1998 Dark Energy Clifford A. Pickover
1998 International Space Station Jim Bell

Introduction

"It is the most persistent and greatest adventure in human history, this search to understand the universe, how it works and where it came from. It is difficult to imagine that a handful of residents of a small planet circling an insignificant star in a small galaxy have as their aim a complete understanding of the entire universe, a small speck of creation truly believing it is capable of comprehending the whole."

—Murray Gell-Mann, in John Boslough's *Stephen Hawking's Universe*, 1989

The Scope of Science and Mathematics

Today scientists and mathematicians roam far and wide, studying an awesome variety of topics and fundamental laws in order to understand the behavior of nature, the universe, and the very fabric of reality. Physicists ponder multiple dimensions, parallel universes, and the possibilities of wormholes connecting different regions of space and time. Biologists, physicians, and ethicists consider organ transplants, gene therapy, and cloning, while the studies of DNA and the human genome yield secrets about fundamental aspects of life itself. The usefulness of mathematics allows us to build spaceships and investigate the geometry of our universe. Interestingly, a significant number of discoveries in basic physics have also led to a range of medical tools and have helped to reduce human suffering and save lives (for example, X-rays, ultrasonagraphy, magnetic resonance imaging, and more.)

While the discoveries of scientists and mathematicians often lead to new technologies, they also can change our philosophies and the way we look at the world. For example, for many scientists, the Heisenberg Uncertainty Principle means that the physical universe literally does not exist in a determinist form but is rather a mysterious collection of probabilities.

Advances in the understanding of electromagnetism led to the invention of the radio, television, and computers. Understanding of thermodynamics led to the invention of the car.

As will become apparent as you peruse this book, the precise scope of science and mathematics has not been fixed through the ages, nor is it easily delimited. I have taken a rather wide view and have included topics that touch on engineering and applied physics, advances in our understanding of the nature of astronomical objects, and even a few topics that are quite philosophical. Despite this large scope, most areas of science have in common a strong reliance on mathematical tools to aid scientists in their understandings, experiments, and predictions about the natural world.

Albert Einstein once remarked that "the most incomprehensible thing about the world is that it is comprehensible." Indeed, we appear to live in a cosmos that can be described or approximated by compact mathematical expressions and physical laws. However, beyond discovering these laws of nature, scientists often delve into some of the most profound and mind-boggling concepts that humans have ever contemplated—topics ranging from relativity and quantum mechanics to string theory and the nature of the Big Bang from which the universe evolved. Quantum mechanics gives us a glimpse of a world that is so strangely counterintuitive that it raises questions about space, time, information, and cause and effect. However, despite the seemingly mysterious results of quantum mechanics, this field of study is applied in numerous fields and in technologies that include the laser, the transistor, the microchip, and magnetic resonance imaging.

This book is also about the *people* behind many of the great ideas of science and mathematics. Physics, for example, is the foundation of modern science, and it has fascinated men and women for centuries and included some of the world's greatest and most intriguing minds, such as Isaac Newton, James Clerk Maxwell, Marie Curie, Albert Einstein, Richard Feynman, and Stephen Hawking. These individuals have helped change the way we think about at the universe. In the fields of medicine, Ambroise Paré and Joseph Lister changed how we deal with injuries and diseases. Consider the use of ligatures to stem the flow of blood during surgeries, for example, as performed by the French surgeon Paré (1510–1590) or the use of antiseptic surgery, which was promoted by British surgeon Lister (1827–1912) and his use of carbolic acid (now called phenol) as a means for sterilizing wounds and surgical instruments, which dramatically reduced post-operative infections. Beyond these kinds of practical accomplishments, Marie Curie, the physicist and chemist who conducted groundbreaking research on radioactivity, also reminds us about the adventure in science, stating: “I am among those who think that science has great beauty. A scientist in his laboratory is not only a technician: he is also a child placed before natural phenomena which impress him like a fairy tale. . . . If I see anything vital around me, it is precisely that spirit of adventure, which seems indestructible and is akin to curiosity.”

Welcome to *The Science Book*, which ranges from theoretical and eminently practical topics to the odd and perplexing. We’ll encounter mysterious *dark energy*, which may one day tear apart galaxies and end the universe in a terrible cosmic rip, and the *blackbody radiation law*, which started the science of quantum mechanics. The Copernican System, evolution, antibiotics, the Periodic Table, the steam engine, and anesthesia all make an appearance in this book. We’ll travel through time and space, leaping through the ages, from the creation of bronze (c. 3300 BCE), iron smelting (c. 1300 BCE), and the development of Roman concrete (c. 125) to the first industrial synthesis of polyethylene (1933), which is the most common plastic in the world today. In biological arenas, we’ll witness the cultivation of wheat and the domestication of animals, and explore the fossil record, food webs, and insect dance language.

It may seem unusual to some readers to see so many mathematical entries in a book about science. However, I have intentionally emphasized mathematics. After all, mathematics has permeated every field of scientific endeavor and plays an invaluable role in biology, physics, chemistry, economics, sociology, and engineering. Mathematics can be used to help explain the colors of a sunset or the architecture of our brains. Mathematics helps us build supersonic aircraft and roller coasters, simulate the flow of Earth’s natural resources, explore subatomic quantum realities, and image faraway galaxies. Mathematics has changed the way we look at the cosmos.

Math is also supremely important in student studies of science and helps pupils better understand scientific principles, assisting those in both high school and college to find relationships between scientific hypotheses and data collected, and to better understand the significance of findings. Papers in technical journals in psychology, biology, engineering, chemistry, physics, geology, and many more areas are replete with formulas, calculations, graphs, statistics, and mathematical models.

In history, mathematical theories have sometimes been used to predict phenomena that were not confirmed until years later. Maxwell's Equations, for example, predicted radio waves. Einstein's field equations suggested that gravity would bend light and that the universe is expanding. Physicist Paul Dirac once noted that the abstract mathematics we study now gives us a glimpse of physics in the future. In fact, his equations predicted the existence of antimatter, which was subsequently discovered. Similarly, mathematician Nikolai Lobachevsky said that "there is no branch of mathematics, however abstract, which may not someday be applied to the phenomena of the real world."

Each book entry is short, at most only a few paragraphs in length. This format allows readers to jump in to ponder a subject, without having to sort through a lot of verbiage. In selecting milestones for this book, I considered whether the scientific milestone was influential in shaping the contemporary world and/or directing the river of humanity's history. The milestones, as a whole, are also meant to provide the general reader with a sense of wonder of the breadth and diversity of scientific discovery and accomplishment. Similarly, the milestones had a strong impact on humanity, culture, and thinking about the world. Finally, I should note these milestones are selected from the Sterling Milestone Series, which include my own three books—*The Math Book*, *The Physics Book*, and *The Medicine Book*—as well as entries from *The Psychology Book, The Biology Book*, *The Chemistry Book*, *The Space Book*, and *The Engineering Book*. Readers are urged to consult these books for additional milestones in these fields.

Purpose and Chronology

Examples of scientific and mathematical principles are all around us. My goal in compiling *The Science Book* is to provide a wide audience with a brief guide to important ideas and thinkers, with entries short enough to digest in a few minutes. Most entries are ones that interested me personally. Alas, not all of the great science and mathematics milestones are included in this book in order to prevent the book from growing too large. Thus, in celebrating the wonders of science in this short volume, I have been forced to omit many important scientific marvels. Nevertheless, I believe that I have included a majority of those with historical significance and that have had a strong influence on science, society, or human thought. Occasional text in bold type points the reader to related entries. Additionally, a small “See also” section near the bottom of each entry helps weave entries together in a web of interconnectedness and may help the reader traverse the book in a playful quest for discovery.

The Science Book reflects my own intellectual shortcomings, and while I try to study as many areas of science as I can, it is difficult to become fluent in all aspects, and this book clearly reflects my own personal interests, strengths, and weaknesses.

I am responsible for the choice of pivotal entries included in this book and, of course, for any errors and infelicities. This is not a comprehensive or scholarly dissertation, but rather it is intended as recreational reading for students of science and mathematics and interested lay people. I welcome feedback and suggestions for improvement from readers, as I consider this an ongoing project and a labor of love.

This book is organized chronologically, according to the year associated with an entry. For many entries, we used dates that are associated with the discovery of a concept or property. Of course, dating of entries can be a question of judgment when more than one individual made a contribution. Often, the earliest date is listed where appropriate, but sometimes a date refers to when a concept gained particular prominence. Many of the older dates in this book, including the “bce dates,” are only approximate. Because this book has entries ordered chronologically, be sure to use the index when hunting for a favorite concept, which may be discussed in entries that you might not have expected.

Who knows what the future of science and mathematics will offer? Toward the end of the nineteenth century, the prominent physicist William Thomson, also known as Lord Kelvin, proclaimed the end of physics. He could never have foreseen the rise of quantum mechanics and relativity—and the dramatic changes these areas would have on the field of physics. Physicist Ernest Rutherford, in the early 1930s, said of atomic energy: “Anyone who expects a source of power from the transformation of these atoms is talking moonshine.” In short, predicting the future of the ideas and applications of physics is difficult, if not impossible.

In closing, let us note that discoveries in science and mathematics provide a framework in which to explore the subatomic and supergalactic realms, and the concepts of physics allow scientists to make predictions about the universe. Many fields in this book cover areas in which philosophical speculation can provide a stimulus for scientific breakthroughs. Thus, the discoveries in this book are among humanity’s greatest achievements. For me, science and mathematics cultivate a perpetual state of wonder about the limits of thoughts, the workings of the universe, and our place in the vast space-time landscape that we call home. The biological and medical entries similarly coax us to wonder about the functioning of the tissues and cells—and provide hope that most of the horrific health ravages of humankind will one day be a thing of the past.

Our brains, which evolved to make us run from lions on the African savanna, may not be constructed to penetrate the infinite veil of reality. We may need mathematics, science, computers, brain augmentation, and even literature, art, and poetry to help us tear away the veils. For those of you who about to embark on reading the *The Science Book* from cover to cover, look for the connections, gaze in awe at the evolution of ideas, and sail on the shoreless sea of imagination.

—Clifford A. Pickover

c. 18,000 BCE

Ishango Bone • *Clifford A. Pickover*

In 1960, Belgian geologist and explorer Jean de Heinzelin de Braucourt (1920–1998) discovered a baboon bone with markings in what is today the Democratic Republic of the Congo. The Ishango bone, with its sequence of notches, was first thought to be a simple tally stick used by a Stone Age African. However, according to some scientists, the marks suggest a mathematical prowess that goes beyond counting of objects.

The bone was found in Ishango, near the headwaters of the Nile River, the home of a large population of upper Paleolithic people prior to a volcanic eruption that buried the area. One column of marks on the bone begins with three notches that double to six notches. Four notches double to eight. Ten notches halve to five. This may suggest a simple understanding of doubling or halving. Even more striking is the fact that numbers in other columns are all odd (9, 11, 13, 17, 19, and 21). One column contains the prime numbers between 10 and 20, and the numbers in each column sum to 60 or 48, both multiples of 12.

A number of tally sticks have been discovered that predate the Ishango bone. For example, the Swaziland Lebombo bone is a 37,000-year-old baboon fibula with 29 notches. A 32,000-year-old wolf tibia with 57 notches, grouped in fives, was found in Czechoslovakia. Although quite speculative, some have hypothesized that the markings on the Ishango bone form a kind of lunar calendar for a Stone Age woman who kept track of her menstrual cycles, giving rise to the slogan “menstruation created mathematics.” Even if the Ishango was a simple bookkeeping device, these tallies seem to set us apart from the animals and represent the first steps to symbolic mathematics. The full mystery of the Ishango bone can’t be solved until other similar bones are discovered.

SEE ALSO Dice (c. 3000 BCE), Sieve of Eratosthenes (c. 240 BCE), Antikythera

Mechanism (c. 125 BCE) Slide Rule (1621).

The Ishango baboon bone, with its sequence of notches, was first thought to be a simple tally stick used by a Stone Age African. However, some scientists believe that the marks suggest a mathematical prowess that goes beyond counting of objects.

c. 11,000 BCE

Wheat: The Staff of Life • *Michael C. Gerald with Gloria E. Gerald*

Wheat was one of the first crops to be cultivated and stored on a large-scale basis, transforming hunter-gathers into farmers, and it was instrumental in the establishment of city-states leading to the Babylonian and Assyrian empires. Wheat originally grew wild in the Fertile Crescent of the Middle East and in southwestern Asia. The archeological evidence traces the origins of wheat to wild grasses, such as wild emmer (*Triticum dicoccum*), which was gathered for food in Iraq in 11,000 BCE, and einkorn (*T. monococcum)*, grown in Syria 7800–7500 BCE. Wheat was farmed in the Nile Valley of Egypt before 5000 BCE, where Joseph of the Hebrew Bible was overseeing grain stores in 1800 BCE.

A natural hybrid, wheat was derived from cross-pollination of grains. Over thousands of years, farmers and breeders have cross-hybridized grains to maximize the qualities they deemed most desirable. During the nineteenth century, single genetic strains were selectively produced that possessed the traits they were seeking. With a growing understanding of Mendelian inheritance, two lines were crossbred, and the progeny inbred for ten or more generations to obtain and maximize specific characteristics. The twentieth century saw the development and planting of hybrids selected on such desirable characteristics as large kernels, short straw, hardiness to cold, and resistance to insects and to fungal, bacterial, and viral diseases.

In recent decades, bacteria have been used to transfer genetic information to produce transgenic wheat. Such genetically modified crops (GMC) have been engineered to produce greater yields, require less nitrogen to grow, and offer greater nutritional value. In 2012, the whole genome of bread wheat was completed and found to have 96,000 genes. This marks an important step in continuing the production of genetically modified wheat, in which more specific desirable characteristics can be inserted in specific loci on the wheat chromosomes.

As rice is a dietary staple in Asia, so is wheat in Europe, North America, and western Asia. Wheat is the most widely consumed cereal grain in the world, and world trade in wheat is greater than all other crops combined.

SEE ALSO Agriculture (c. 10,000 BCE), Domestication of Animals (c. 10,000 BCE), Rice Cultivation (c. 7000 BCE) Green Revolution (1961).

This Chinese farmer is carrying bushels of dry wheat, as did his ancestors for thousands of years.

c. 10,000 BCE

Agriculture • *Michael C. Gerald with Gloria E. Gerald*

From small groups of hunter-gathers living off the land and foraging berries and other edible plants, agriculture, a type of applied biology, evolved to domestication and cultivation of crops. This active involvement originated at different times and places, and to various extents based on environmental conditions: archeological evidence suggests its origin dated from the end of the Ice Age, as early as 14,500 to 12,000 years ago. The earliest agricultural successes coexisting with the rise of great ancient civilizations appeared in major river valleys where the annual river flooding not only provided water but also a consistent source of silt, a natural fertilizer. These included the birthplace of agriculture in the Fertile Crescent between the Tigris and Euphrates Rivers in Mesopotamia and the Nile in Egypt; Indus in India; and the Huang in China.

Explanations for the adoption of agriculture and its consequences vary: Some experts contend that it was intended to meet the increasing food needs in ever-burgeoning populations, needs that could not be satisfied by food gathering or hunting. Alternatively, agriculture may not have originated in response to food scarcity but rather that the population in a given area increased significantly only after stable sources of food had been established. Evidence supporting each has been adduced. Whereas in the Americas, villages sprang up after the development of crops, villages and towns in Europe appeared earlier than or at the same time as agricultural advances.

Agricultural success depended not only upon the whims of nature providing favorable climatic conditions but also upon the ability of early farmers to utilize irrigation, crop rotation, fertilizers, and domestication—the conscious selection of developing plants whose characteristics increased their utility. Tools intended for the simple acquisition of wild foods were replaced by those for production, such as the plow and those powered by animals. The earliest domesticated crops include rye, wheat, and figs in the Middle East; rice and millet in China; wheat and some legumes in the Indus Valley; maize, potatoes, tomatoes, pepper, squash, and beans in the Americas; and wheat and barley in Europe.

SEE ALSO Domestication of Animals (c. 10,000 BCE), Rice Cultivation (c. 7000 BCE) Artificial Selection (Selective Breeding) (1760), Green Revolution (1961).

The National Grange of the Order of Patrons of Husbandry, an association of farmers, was founded in the United States in 1867 to promote community wellness and agriculture. This 1873 poster, "Gift for the Grangers," promotes the organization through idyllic scenes of farm life. In 1870, 70–80 percent of the US population was employed in agriculture; by 2008, this number had dwindled to only 2–3 percent.


GIFT FOR THE GRANGERS.
"I PAY FOR ALL"
FAITH,
HOPE,
CHARITY,
FIDELITY.

c. 10,000 BCE

Domestication of Animals • *Michael C. Gerald with Gloria E. Gerald*

Domesticated animals were initially developed from species that were social in the wild and could breed in captivity, thus allowing genetic modifications to increase those traits that are advantageous to humans. Depending upon the species, such desirable traits might include: being docile and easy to control; having the ability to produce more meat, wool, or fur; and suitability for traction, transportation, pest control, assistance, companionship, or as a form of currency.

The most familiar domesticated animal, the dog (*Canis lupus familiaris*), is a subspecies of the gray wolf (*Canis lupis*), with the oldest fossil remains showing a split in their lineage some 35,000 years ago. Dogs were the first animals to be domesticated with the earliest evidence being a jawbone found in a cave in Iraq and dating back some 12,000 years. Images on Egyptian paintings, Assyrian sculpture, and Roman mosaics show that even in ancient times, domestic dogs were of many sizes and shapes. The first dogs were domesticated by hunter-gatherers but their job description has since been expanded beyond hunting to include herding, protection, pulling loads, aiding police and the military, assisting handicapped individuals, serving as human food, and providing loyal companionship. The American Kennel Club now lists 175 breeds, with most only several hundred years old.

Around 10,000 years ago, sheep and goats were domesticated in southwest Asia. While alive, they served as a source of manure for crop fertilization and, when dead, as a regular supply of food, leather, and wool. Researchers have long been puzzled about the origins and evolution of the domestic horse (*Equus ferus caballus*), whose wild ancestor first appeared 160,000 years ago and is now extinct. Based on archeological and genetic evidence, including bit wear on horse teeth that were found at sites associated with the ancient

Botai culture, in 2012 researchers concluded that their domestication dates back some 6,000 years in the western Eurasian Steppe (Kazakhstan). As they were domesticated, these early horses were regularly bred with wild horses to provide meat and skin and later to play an essential role in war, transportation, and sport.

SEE ALSO Agriculture (c. 10,000 BCE) Artificial Selection (Selective Breeding) (1760), Darwin’s Theory of Natural Section (1859).

Dogs, which have all evolved from the gray wolf, were the first domesticated animals and have been the working partner and loyal companion of humans for some 12,000 years. They are now commonly functionally categorized as companion, guarding, hunting, herding, and working dogs.

c. 7000 BCE

Rice Cultivation • *Michael C. Gerald with Gloria E. Gerald*

FEEDING ASIA. Rice is among the oldest and world's most important economic botanical food crop. It is the largest source of calories for the 3.3 billion people of Asia, providing 35–80 percent of their total caloric intake. But, while rice is nutritious, it is not sufficient to serve as the main food source. The worldwide popularity of rice as a food is attributed, in part, to its ability to be grown in areas as varied as flooded plains to deserts and in all continents, except Antarctica. China and India are the major rice-producing and consuming countries.

Some 12,000–16,000 years ago, rice grains were initially gathered and consumed by prehistoric people in the world's humid tropical and subtropical regions. Wild cultivated prototypes of rice, which descended from wild grasses, are members of the taxon family *Poaceae* (also called *Gramineae*). Based on genetic evidence, recent reports reveal that rice cultivation first occurred in China between 8,200 and 13,500 years ago. From China, cultivation spread to India, then to western Asia and Greece, brought by the armies of Alexander the Great in 300 BCE. The most popular cultivated rices are *Oryza satliva japonica* (Asian rice and, by far, the most common) and *Oryza glaberrima indica* (African rice), both of which were domesticated from a common origin.

The rice plants have an outer coating that protects the rice grain, the fruit of the plant. Seeds are milled to remove the chaff (outer husk) to produce brown rice. If milling is continued, and the rest of the husk and grain removed, white rice is left. Brown rice is more nutritious, containing proteins, minerals, and thiamine (vitamin B_1), while white rice mainly contains carbohydrates and is virtually devoid of thiamine. Beriberi results from a nutritional deficiency in thiamine, which has been historically endemic in

Asian populations, who favor polished white rice because it has a longer shelf life and is not historically associated with poverty. Among cereals, rice is low in sodium and fat, and free of cholesterol, making it a healthy food choice.

SEE ALSO Wheat: The Staff of Life (c. 11,000 BCE), Agriculture (c. 10,000 BCE) Artificial Selection (Selective Breeding) (1760).

Rice is the world's most important food crop and provides the greatest proportion of calories to the people of Asia. Although this crop is typically grown on flooded plains, such as this one in Thailand, it can also be cultivated in deserts.Recent evidence suggests that rice may have actually been domesticated independently on three continents: Asia, Africa, and South America.

c. 5000 BCE

Birth of Cosmology • *Jim Bell*

In Greek, *kosmos* means “the universe,” and thus our modern word *cosmology* refers to the study of the nature, origin, and evolution of the universe. In the classical context, a society’s cosmology refers to its worldview or its way of thinking about where its people came from, why they are there, and where they are going. Civilizations throughout human history have created and nourished their cosmologies through creation stories, mythology, religion, philosophy, and, most recently, science.

We often hear (or read) such platitudes about how humanity has always been looking to the stars, or how our distant ancestors must have pondered the heavens in this way or that. While it’s fun to speculate, it’s impossible to know what prehistoric people were really thinking because (by definition) there’s no record of prehistory. That’s one reason why the oldest archaeological artifacts that depict or represent astronomical themes are so important: they provide some real data with which to try to understand how ancient people viewed the universe.

The oldest preserved evidence of a civilization pondering the heavens comes from the Sumerians, in their partial star maps or pieces of crude astronomical instruments that some scholars believe date to between 5,000 and 7,000 years ago. Even the scant fragments of information available from that time reveal a significant degree of sophistication in the Sumerians’ understanding of the motions of the Sun, Moon, major planets, and stars. Perhaps this is not surprising: the Sumerians built the first city-states supported by the cultivation of crops by a year-round, nonmigratory population. Knowing how to read the sky translated directly into knowing when to plant, irrigate, and harvest, and a stable food supply gave them time to invent writing, arithmetic, geometry, and algebra.

Sumerian cosmology appears to have been the first to make gods of the heavenly bodies, a practice inherited by later Babylonian, Greek, Roman, and other cosmologists. Sumerian cosmology also espoused the idea of many heavens and many Earths in what was a decidedly nongeocentric universe. It’s a worldview that resonates—surprisingly—with modern cosmological thinking, as the reality seems to be a universe without any center at all and apparently brimming with many Earths.

SEE ALSO Egyptian Astronomy (c. 2500 BCE) Sun-Centered Universe (1534), Telescope (1608), Newton’s Prism (1672), Hubble Telescope (1990).

Reconstruction of an ancient Sumerian star chart from 3300 BCE known as the planisphere of Nineveh, which is believed to be one of the oldest astronomical instruments and data sets ever discovered.

c. 3300 BCE

Bronze • *Derek B. Lowe*

Bronze is the first metal that gets its own age, which began around 3300 BCE in Mesopotamia. Other metals were certainly in use before it—especially copper—but the addition of a small amount of tin to existing copper technology changed everything. Bronze was a step up in hardness, durability, and resistance to corrosion. Unfortunately, tin and copper ores generally aren't found together, which meant that an area rich in one ingredient had to trade for the other. Beginning around 2000 BCE, tin from Cornwall (southwest Britain) was in such demand that it turned up in many eastern Mediterranean archaeological sites, thousands of miles away.

We don't know much about these early chemists and metallurgists, but it's clear that they experimented with whatever they had on hand. Bronze alloys have turned up with all sorts of other metals in them—lead, arsenic, nickel, antimony, and even precious metals like silver. Those must have taken especially large amounts of nerve to add to the mix, since it was almost certain at the time that you would never see them again (the techniques to repurify such metals would not arrive for many centuries).

And thus, the long human adventure with metallurgy began—one that is nowhere near over. Bronze itself has been improved over the years—the Greeks added more lead to make the resulting alloy easier to work with, and the addition of zinc takes you into the various forms of brass. Modern bronzes often have aluminum or silicon in them, which were completely unknown to the ancients. If you want to see real, old-fashioned bronze of a kind that would have been recognized thousands of years ago, take a close look at a drum kit. Bronze has been the preferred metal for bells and cymbals for hundreds of years. The more tin in the mix, the lower the timbre, but there is no record of what adding arsenic or silver might do to the sound.

SEE ALSO Iron Smelting (c. 1300 BCE) Roman Concrete (c. 126), Bessemer Process

(1855).

This ancient, Chinese bronze bell may have been part of a larger set, tuned and shaped to produce different notes. Casting bronze instruments to such specific tolerances is a serious technical challenge.

c. 3000 BCE

Dice • *Clifford A. Pickover*

Imagine a world without random numbers. In the 1940s, the generation of statistically random numbers was important to physicists simulating thermonuclear explosions, and today, many computer networks employ random numbers to help route Internet traffic to avoid congestion. Political poll-takers use random numbers to select unbiased samples of potential voters.

Dice, originally made from the anklebones of hoofed animals, were one of the earliest means for producing random numbers. In ancient civilizations, the gods were believed to control the outcome of dice tosses; thus, dice were relied upon to make crucial decisions, ranging from the selection of rulers to the division of property in an inheritance. Even today, the metaphor of God controlling dice is common, as evidenced by astrophysicist Stephen Hawking's quote, "Not only does God play dice, but He sometimes confuses us by throwing them where they can't be seen."

The oldest-known dice were excavated together with a 5,000-year-old backgammon set from the legendary Burnt City in southeastern Iran. The city represents four stages of civilization that were destroyed by fires before being abandoned in 2100 BCE At this same site, archeologists also discovered the earliest-known artificial eye, which once stared out hypnotically from the face of an ancient female priestess or soothsayer.

For centuries, dice rolls have been used to teach probability. For a single roll of an n-sided die with a different number on each face, the probability of rolling any value is $1/n$. The probability of rolling a particular sequence of i numbers is $1/n^i$. For example, the chance of rolling a 1 followed by a 4 on a traditional die is $1/6^2 = 1/36$. Using two traditional dice, the probability of throwing any given sum is the number of ways to throw that sum divided by the total number of combinations, which is why a sum of 7 is much more likely than a sum of 2.

SEE ALSO Law of Large Numbers (1713), Normal Distribution Curve (1733), Laplace's *Théorie Analytique des Probabilités* (1812)

Dice were originally made from the anklebones of animals and were among the earliest means for producing random numbers. In ancient civilizations, people used dice to predict the future, believing that the gods influenced dice outcomes.

c. 3000 BCE

Sundial • *Clifford A. Pickover*

> "Hide not your talents. They for use were made. What's a sundial in the shade?"
>
> —Ben Franklin

For centuries, people have wondered about the nature of time. Much of ancient Greek philosophy was concerned with understanding the concept of eternity, and the subject of time is central to all the world's religions and cultures. Angelus Silesius, a seventeenth-century mystic poet, actually suggested that the flow of time could be suspended by mental powers: "Time is of your own making; its clock ticks in your head. The moment you stop thought, time too stops dead."

One of the oldest of time-keeping devices is the sundial. Perhaps ancient humans noticed that the shadows they cast were long in the early morning, grew progressively shorter, and then grew longer again as the evening approached. The earliest known sundial dates to about 3300 BCE and is found engraved in a stone in the Knowth Great Mound in Ireland.

A primitive sundial can be made from a vertical stick in the ground. In the northern hemisphere, the shadow rotates around the stick in a clockwise direction, and the shadow's position can be used to mark the passage of time. The accuracy of such a crude instrument is improved if the stick is slanted so that it points to the Celestial North Pole, or roughly toward the position of the Pole Star. With this modification, the pointer's shadow will not change with the seasons. One common form of sundial has a *horizontal* dial, sometimes used as an ornament in a garden. Because the shadow does not rotate uniformly around the face of this sundial, the marks for each hour are not spaced equally. Sundials may not be accurate for various reasons, including the variable speed of the Earth orbiting the Sun, the use of daylight savings time, and the fact that clock times today are generally kept uniform within time zones. Before the days of wristwatches, people sometimes carried a folding sundial in their pockets, attached to a small magnetic compass to estimate true north.

SEE ALSO Egyptian Astronomy (c. 2500 BCE) Time Travel (1949), Radiocarbon Dating (1949), Atomic Clocks (1955).

People have always wondered about the nature of time. One of the most ancient of timekeeping devices is the sundial.


GROW
ALONG
BEST
OLD
WITH
IS YET

c. 3000 BCE

Sutures • *Clifford A. Pickover*

Galen of Pergamon (129–199), **al-Zahrawi** (936–1013), **Joseph Lister** (1827–1912)

"In an era of escalating surgical technology," writes surgeon John Kirkup, "it is tempting to downgrade the minor craft of wound closure when compared to more sophisticated operating skills. Indeed, before antiseptic and aseptic procedures were established, closure was a source of many disasters. Even today, successful operations depend on prompt reliable healing of skin, bowel, bone, tendon and other tissues, and neither healing nor a cosmetically acceptable scar can be guaranteed."

Today, a surgical suture usually refers to a needle with an attached length of thread that is used to stitch together the edges of a wound or surgical cut. However, through history, the suture has taken many forms. Needles have been made of bone or metal. Sutures were made of materials such as silk or catgut (sheep intestines). Sometimes, large ants were used to pinch wounds together. After the ant's pincers had bitten into the flesh and closed an opening, the body of the ant was removed, leaving just the head and closed pincers behind. The ancient Egyptians used linen and animal sinew to close wounds, and the earliest reports of such suturing date back to 3000 BCE. Galen, the second-century Greco-Roman physician, used sutures made from animal materials, as did the Arab surgeon al-Zahrawi. British surgeon Joseph Lister investigated ways to sterilize catgut, a suture material the body gradually absorbed. In the 1930s, a major manufacturer of catgut sutures used 26,000 sheep intestines in a single day. Today, many sutures are made from absorbable or nonabsorbable synthetic polymer fibers, and eyeless needles may be premounted to the suture in order to lessen trauma to body tissues during the threading process. Adhesive liquids are also used to assist in wound closure.

Depending on use, sutures vary in width, with some smaller than the diameter of a human hair. In the nineteenth century, surgeons often preferred to cauterize (burn) wounds, an often gruesome process, rather than risk the patients dying from infected sutures.

SEE ALSO Paré's "Rational Surgery" (1545), Antiseptics (1865), Laser (1960).

Surgeon's gloved hand holding a needle holder with an atraumatic curved cutting needle attached to a 4-0 monofilament nonabsorbable synthetic suture.

c. 2500 BCE

Egyptian Astronomy • *Jim Bell*

The great pyramids of Giza are a monument to the technological (and labor management) prowess of ancient Egyptian civilization. They are also testaments to the designers' astronomical skill, which figured prominently in Egyptian society and religion 4,500 years ago.

Because the earth's spin axis slowly precesses, or wobbles like a spinning top, back in 2500 BCE Polaris was not the North Star. Indeed, much like the skies near our south celestial pole today, there was no bright star near the north celestial pole in those days. To the pharaohs, astrologers, and commoners, the sky at night appeared to spin around a vortex-like dark hole, thought to be a gateway to the heavens. In ancient Egypt, this gateway was located about 30 degrees above the northern horizon, and so the pyramids were carefully aligned to the north, with a small shaft leading from the pharaoh's main burial chamber to the outside, pointing directly into the center of the gateway. If the plan was to join the gods in the afterlife, why not go in through the main door?

Egyptian astrologers also played an important role in developing a rather sophisticated calendar system that was already well established by the time the pyramids were being built. A new year was defined by the first sighting of the brightest star in the sky, Sirius (Sopdet to the Egyptians), just before sunrise in midsummer. The year was divided into 12 months of 30 days each, with 5 extra days of worship or parties tacked onto the end for a 365-day year. They also knew from carefully observing and recording star positions on different dates that they needed to add an extra day every fourth year—what we call a leap day—to keep their calendar synced to the motions of the sky. The predawn rising times of a number of bright stars were tracked in order to determine times for major religious festivals, as well as to plan for the annual floods of the Nile.

The pyramid shape itself may even represent a facet of ancient Egyptian cosmology, as some myths claim that the god of creation, Atum, lived within a pyramid that, along with the land, had emerged from the primordial ocean.

SEE ALSO Birth of Cosmology (c. 5000 BCE), Sundial (c. 3000 BCE) Sun-Centered Universe (1543).

The great pyramids of Giza, burial places of the pharaohs and astronomical pointers to the presumed gateway to the heavens at the north celestial pole. These were the largest human-made structures in the world for nearly 4,000 years.

c. 1850 BCE

Arch • *Clifford A. Pickover*

In architecture, an arch is a curved structure that spans a space while supporting weight. The arch has also become a metaphor for extreme durability created by the interaction of simple parts. The Roman philosopher Seneca wrote, "Human society is like an arch, kept from falling by the mutual pressure of its parts." According to an ancient Hindu proverb, "An arch never sleeps."

The oldest existing arched city gate is the Ashkelon gate in Israel, built c. 1850 BCE of mud-brick with some calcareous limestone. Mesopotamian brick arches are even older, but the arch gained particular prominence in ancient Rome, where it was applied to a wide range of structures.

In buildings, the arch allows the heavy load from above to be channeled into horizontal and vertical forces on supporting columns. The construction of arches usually relies upon wedge-shaped blocks, called voussoirs, that precisely fit together. The surfaces of neighboring blocks conduct loads in a mostly uniform manner. The central voussoir, at the top of the arch, is called the keystone. To build an arch, a supporting wooden framework is often used until the keystone is finally inserted, locking the arch in place. Once inserted, the arch becomes self-supporting. One advantage of the arch over earlier kinds of supporting structures is its creation from easily transported voussoirs and its spanning of large openings. Another advantage is that gravitational forces are distributed throughout the arch and converted to forces that are roughly perpendicular to voussoirs' bottom faces. However, this means that the base of the arch is subject to some lateral forces, which must be counterbalanced by materials (e.g. a brick wall) located at the bottom sides of the arch. Much of the force of the arch is converted to compressional forces on the voussoirs—forces that stones, concrete, and other materials can easily withstand. Romans mostly constructed semicircular arches, although other shapes are possible. In Roman aqueducts, the lateral forces of neighboring arches served to counteract each other.

SEE ALSO Pulley (c. 230 BCE), Gears (c. 50), Roman Concrete (c. 126).

The arch allows the heavy load from above to be channeled into horizontal and vertical forces. Arches usually rely upon wedge-shaped blocks, called voussoirs, that fit closely together as in these ancient Turkish arches.

c. 1650 BCE

Rhind Papyrus • *Clifford A. Pickover*

Ahmes (c. 1680 BCE–c. 1620 BCE), **Alexander Henry Rhind** (1833–1863)

The Rhind Papyrus is considered to be the most important known source of information concerning ancient Egyptian mathematics. This scroll, about a foot (30 centimeters) high and 18 feet (5.5 meters) long, was found in a tomb in Thebes on the east bank of the river Nile. Ahmes, the scribe, wrote it in hieratic, a script related to the hieroglyphic system. Given that the writing occurred in around 1650 BCE, this makes Ahmes the earliest-named individual in the history of mathematics! The scroll also contains the earliest-known symbols for mathematical operations—*plus* is denoted by a pair of legs walking toward the number to be added.

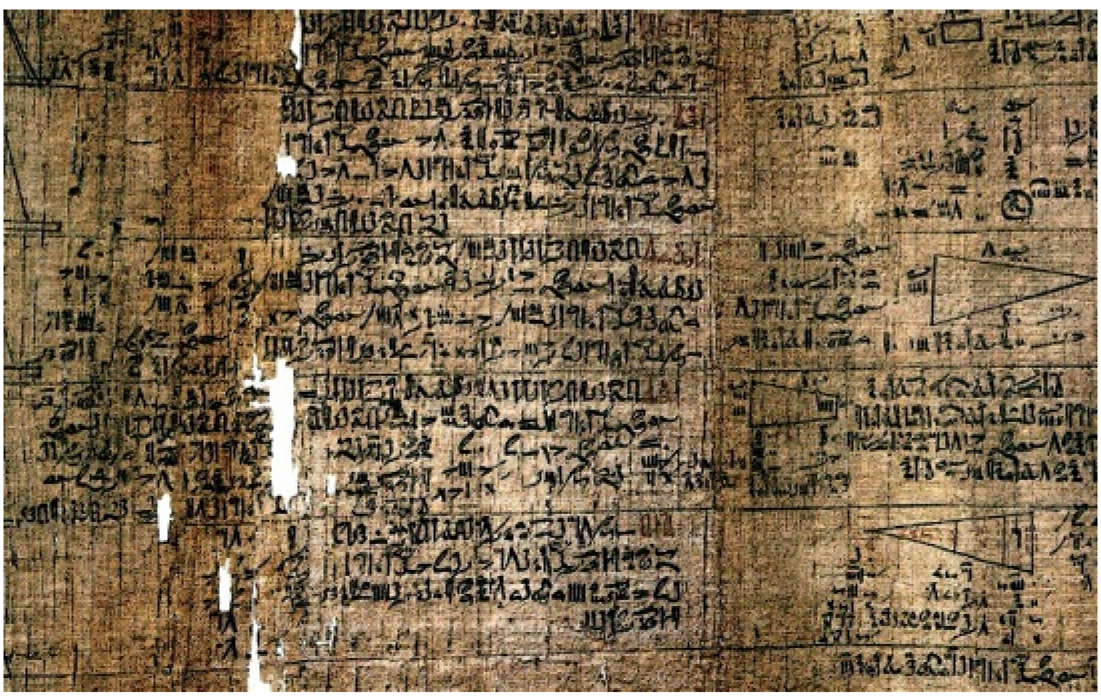
In 1858, Scottish lawyer and Egyptologist Alexander Henry Rhind had been visiting Egypt for health reasons when he bought the scroll in a market in Luxor. The British Museum in London acquired the scroll in 1864.

Ahmes wrote that the scroll gives an "accurate reckoning for inquiring into things, and the knowledge of all things, mysteries . . . all secrets." The content of the scroll concerns mathematical problems involving fractions, arithmetic progressions, algebra, and pyramid geometry, as well as practical mathematics useful for surveying, building, and accounting. The problem that intrigues me the most is Problem 79, the interpretation of which was initially baffling.

Today, many interpret Problem 79 as a puzzle, which may be translated as "Seven houses contain seven cats. Each cat kills seven mice. Each mouse had eaten seven ears of grain. Each ear of grain would have produced seven hekats (measures) of wheat. What is the total of all of these?" Interestingly, this indestructible puzzle meme, involving the number 7 and animals, seems to have persisted through thousands of years! We observe something quite similar in Fibonacci's *Liber Abaci* (*Book of Calculation*), published in 1202, and later in the St. Ives puzzle, an Old English children's rhyme involving 7 cats.

SEE ALSO Ishango Bone (c. 18,000 BCE), Pythagorean Theorem and Triangles (c. 600 BCE), Fibonacci's *Liber Abaci* (1202).

The Rhind Papyrus is the most important source of information concerning ancient Egyptian mathematics. The scroll, a portion of which is shown here, includes mathematical problems involving fractions, arithmetic progressions, algebra, geometry, and accounting.



c. 1300 BCE

Iron Smelting • *Derek B. Lowe*

The Iron Age definitively replaced the Bronze Age, so you would assume that the newly available iron must have been clearly superior. Not so—good bronze was harder and much more corrosion-resistant. However, major disturbances and population movements in the Mediterranean and Near East around 1300 BCE may have disrupted the metal trade that bronze-working depended on. Iron ore was much easier to come by, but higher-temperature furnaces were needed to smelt it, and these often depended on forced air. Iron production was thus, sometimes, a seasonal event, with furnaces built to take advantage of monsoons and other dependable winds. Objects made of iron from before 1300 BCE are known but uncommon, and many of these are not even from our own planet—produced from solid nickel-iron meteorites, they must have been very valuable objects indeed.

Given a chance, iron will react with oxygen to produce rust (iron oxide), and smelting iron ore is basically the reverse process. The early iron-smelting device, a clay or stone furnace with air inlet tubes, was called a bloomery. Charcoal and iron ore were heated, producing a lump of crude smelted iron (the bloom) in the bottom of the furnace. This was a laborious process, since the bloom needed further heating, and lumps of impurities had to be beaten out before it could be useful. Still, iron technology spread rapidly, and it seems to have been discovered independently in several locations, including India and sub-Saharan Africa. Ancient wind-driven iron furnaces evolved into the modern blast furnace—in which ore is fed in continuously from the top and has its oxygen stripped away by contact with carbon monoxide gas of ferocious temperatures—as early as the first or second century BCE in China.

Iron's properties change dramatically depending on what is mixed into it. Careful addition of some of the charcoal's carbon produces steel—a superior metal in every way—but this was a job for experienced craftsmen: too little carbon produced soft wrought iron, while too much carbon yielded a very hard metal that is too brittle for most uses. Now, the varieties of iron alloys and steels in modern metallurgy are almost too many to count.

SEE ALSO Bronze (c. 3300 BCE) Bessemer Process (1855), Plastic (1856).

A modern blast furnace can produce molten iron on a scale that ancient craftsmen could only dream of. But by any route, ironworking has always been a very energy-intensive process.

c. 1000 BCE

Olmec Compass • *Clifford A. Pickover*

Michael D. Coe (b. 1929), **John B. Carlson** (b. 1945)

For many centuries, navigators have used compasses with magnetized pointers for determining the Earth's magnetic north pole. The *Olmec compass* in Mesomerica may represent the earliest known compass. The Olmecs were an ancient pre-Columbian civilization situated in south-central Mexico from around 1400 BCE to 400 BCE and famous for the colossal artwork in the form of heads carved from volcanic rock.

American astronomer John B. Carlson used Radiocarbon Dating methods of the relevant layers of an excavation to determine that a flattened, polished, oblong piece of hematite (iron oxide) had its origin about 1400–1000 BCE. Carlson has speculated that the Olmecs used such objects as direction indicators for astrology and geomancy, and for orienting burial sites. The Olmec compass is part of a polished lodestone (magnetized piece of the mineral) bar with a groove at one end that was possibly used for sighting. Note that the ancient Chinese invented the compass some time before the second century, and the compass was used for navigation by the eleventh century.

Carlson writes in "Lodestone Compass: Chinese or Olmec Primacy?"

> Considering the unique morphology (purposefully shaped polished bar with a groove) and composition (magnetic mineral with magnetic moment vector in the floating plane) of M-160, and acknowledging that the Olmec were a sophisticated people who possessed advanced knowledge and skill in working iron ore minerals, I would suggest for consideration that the Early Formative artifact M-160 was probably

> manufactured and used as what I have called a zeroth-order compass, if not a first-order compass. Whether such a pointer would have been used to point to something astronomical (zeroth-order compass) or to geomagnetic north-south (first-order compass) is entirely open to speculation.

In the late 1960s, Yale University archeologist Michael Coe found the Olmec bar at San Lorenzo in the Mexican state of Veracruz, and it was tested by Carlson in 1973. Carlson floated it on mercury or on water with a cork mat.

SEE ALSO Ampère's Law of Electromagnetism (1825), Faraday's Law of Induction (1831), Telegraph System (1837), Radiocarbon Dating (1949).

In the most general definition, a lodestone refers to a naturally magnetized mineral, such as those used in fragments that ancient people used to create magnetic compasses. Shown here is a lodestone in the Hall of Gems at the National Museum of Natural History, administered by The Smithsonian Institution.

c. 600 BCE

Pythagorean Theorem and Triangles •

Clifford A. Pickover

Baudhayana (c. 800 BCE), **Pythagoras of Samos** (c. 580 BCE–c. 500 BCE)

Today, young children sometimes first hear of the famous Pythagorean theorem from the mouth of the Scarecrow, when he finally gets a brain in MGM's 1939 film version of *The Wizard of Oz*. Alas, the Scarecrow's recitation of the famous theorem is completely wrong!

The Pythagorean theorem states that for any right triangle, the square of the hypotenuse length c is equal to the sum of the squares on the two (shorter) "leg" lengths a and b—which is written as $a^2 + b^2 = c^2$. The theorem has more published proofs than any other, and Elisha Scott Loomis's book *Pythagorean Proposition* contains 367 proofs.

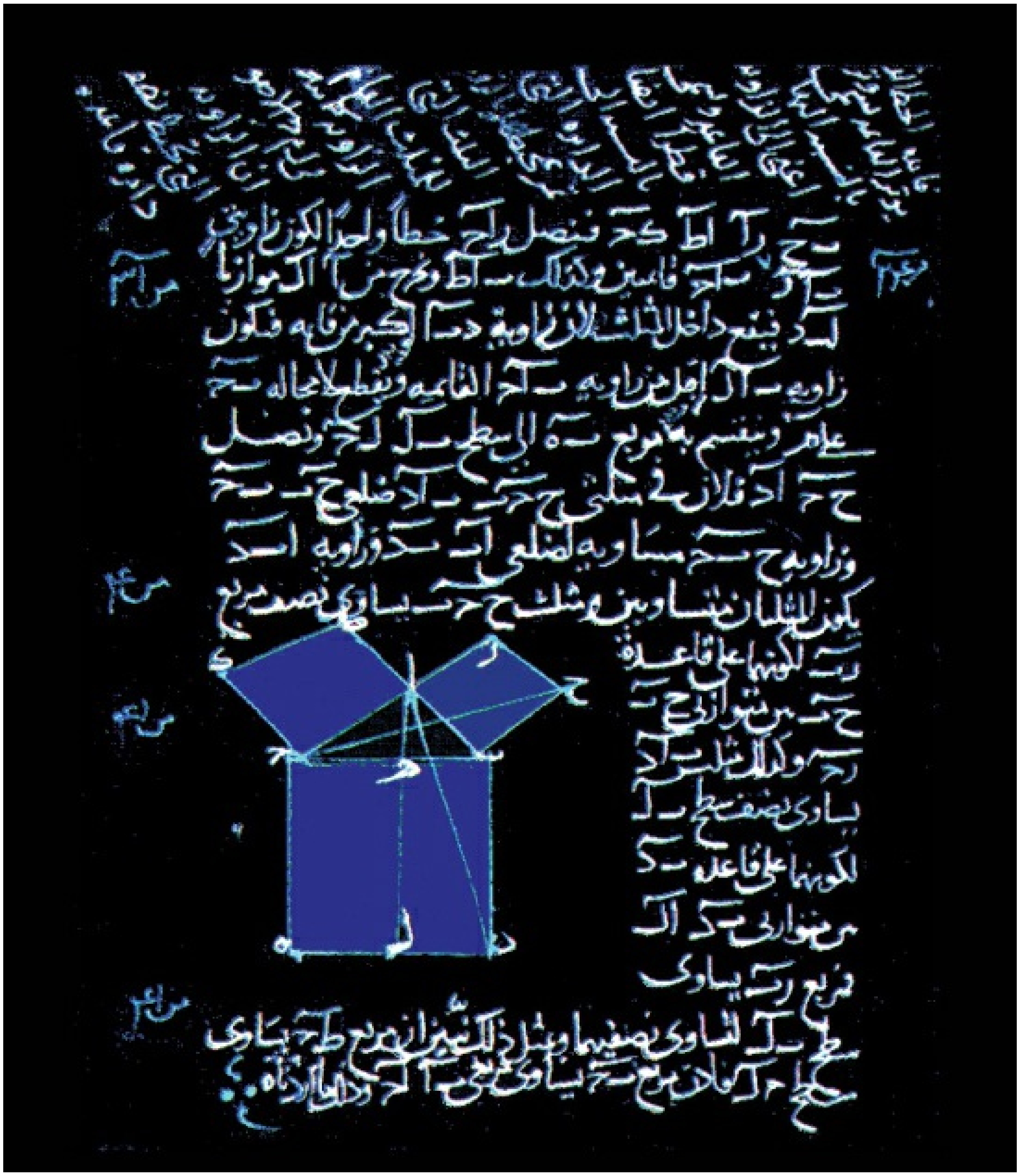
Pythagorean triangles (PTs) are right triangles with integer sides. The "3-4-5" PT— with legs of lengths 3 and 4, and a hypotenuse of length 5—is the only PT with three sides as consecutive numbers and the only triangle with integer sides, the sum of whose sides (12) is equal to double its area (6). After the 3-4-5 PT, the next triangle with consecutive leg lengths is 21-20-29. The tenth such triangle is much larger: 27304197-27304196-38613965.

In 1643, French mathematician Pierre de Fermat (1601–1665) asked for a PT, such that both the hypotenuse c and the sum ($a + b$) had values that were square numbers. It was startling to find that the *smallest* three numbers satisfying these conditions are 4,565,486,027,761, 1,061,652,293,520, and 4,687,298,610,289. It turns out that the second such triangle would be so "large" that if its numbers were represented as feet, the triangle's legs would project from Earth to beyond the sun!

Although Pythagoras is often credited with the formulation of the Pythagorean theorem, evidence suggests that the theorem was developed by the Hindu mathematician Baudhayana centuries earlier around 800 BCE in his book *Baudhayana Sulba Sutra*. Pythagorean triangles were probably known even earlier to the Babylonians.

SEE ALSO Platonic Solids (c. 350 BCE), Golden Ratio (1509), Descartes' *La Geometrie* (1637).

Persian mathematician Nasr al-Din al-Tusi (1201–1274) presented a version of Euclid's proof of the Pythagorean theorem. Al-Tusi was a prolific mathematician, astronomer, biologist, chemist, philosopher, physician, and theologian.



c. 600 BCE

Sewage Systems • *Clifford A. Pickover*

Given the very large variety of diseases that can be caused by sewage or sewage-contaminated water, the development of effective sewage systems deserves an entry in this book. As an example, the following sewage-related diseases are possible dangers in the United States today, and many can cause severe diarrhea: campylobacteriosis (the most common diarrheal illness in the United States, caused by the bacterium *Campylobacter*, which can spread to the bloodstream and cause a life-threatening infection in people with weakened immune systems), cryptosporidiosis (caused by the microscopic parasite *Cryptosporidium parvum)*, diarrheagenic *E. coli (*different varieties of the *Escherichia coli* bacteria), encephalitis (a viral disease transmitted by mosquitoes that often lay eggs in water contaminated by sewage), viral gastroenteritis (caused by many viruses, including rotavirus), giardiasis (caused by the one-celled microscopic parasite *Giardia intestinalis*), hepatitis A (a liver disease caused by a virus), leptospirosis (caused by bacteria), and methaemoglobinaemia (also known as blue-baby syndrome, triggered when infants drink well-water high in nitrates from septic systems).

Other sewage-related diseases include poliomyelitis (caused by a virus) and the following diseases caused by bacteria: salmonellosis, shigellosis, paratyphoid fever, typhoid fever, yersiniosis, and cholera.

This entry is dated to around 600 BCE, which is traditionally thought to be the date of the initial construction of the Cloaca Maxima, one of the world’s most famous early and large sewage systems, constructed in ancient Rome in order to drain local marshes and channel wastes to the River Tiber. However, older sewage disposal systems were built in ancient India, prehistoric Middle East, Crete, and Scotland. Today, sewage treatment often involves various filters and the biological degradation of wastes by microorganisms in a managed habitat, followed by disinfection to reduce the number of microorganisms before the water is discharged into the environment. Disinfectants may include chlorine, ultraviolet light, and ozone. Chemicals are sometimes used to reduce the levels of nitrogen and phosphorus. Prior to sewage systems, city dwellers often threw waste into the streets.

SEE ALSO Zoo Within Us (1683), Semmelweis's Hand Washing (1847), Antiseptics (1865), Chlorination of Water (1910).

The latrines of Housesteads Roman Fort along Hadrian's Wall in the ancient Roman province of Britannia. The flow of water from adjacent tanks flushed away waste matter.

c. 350 BCE

Aristotle's *Organon* • *Clifford A. Pickover*

Aristotle (384 BCE–322 BCE)

Aristotle was a Greek philosopher and scientist, a pupil of Plato, and a teacher of Alexander the Great. The *Organon* (*Instrument*) refers to the collection of six of Aristotle's works on logic: *Categories*, *Prior Analytics*, *De Interpretatione*, *Posterior Analytics*, *Sophistical Refutations*, and *Topics*. Andronicus of Rhodes determined the ordering of the six works around 40 BCE Although Plato (c. 428–348 BCE) and Socrates (c. 470–399 BCE) delved into logical themes, Aristotle actually systematized the study of logic, which dominated scientific reasoning in the Western world for 2,000 years.

The goal of the *Organon* is not to tell readers what is true, but rather to give approaches for how to investigate truth and how to make sense of the world. The primary tool in Aristotle's tool kit is the syllogism, a three-step argument, such as "All women are mortal; Cleopatra is a woman; therefore, Cleopatra is mortal." If the two premises are true, we know that the conclusion must be true. Aristotle also made a distinction between particulars and universals (general categories). *Cleopatra* is a particular term. *Woman* and *mortal* are universal terms. When universals are used, they are preceded by "all," "some," or "no." Aristotle analyzed many possible kinds of syllogisms and showed which of them are valid.

Aristotle also extended his analysis to syllogisms that involved modal logic—that is, statements containing the words "possibly" or "necessarily." Modern mathematical logic can depart from Aristotle's methodologies or extend his work into other kinds of sentence structures, including ones that express more complex relationships or ones that involve more than one quantifier, such as "No women like all women who dislike some women."

Nevertheless, Aristotle's systematic attempt at developing logic is considered to be one of humankind's greatest achievements, providing an early impetus for fields of mathematics that are in close partnership with logic and even influencing theologians in their quest to understand reality.

SEE ALSO Euclid's *Elements* (c. 300 BCE), Bayes' Theorem (1761), Gödel's Theorem (1931).

Italian Renaissance artist Raphael depicts Aristotle (right), holding his Ethics, next to Plato. This Vatican fresco, The School of Athens, *was painted between 1510 and 1511.*


TIMEO
ETIC

c. 350 BCE

Platonic Solids • *Clifford A. Pickover*

Plato (c. 428 BCE–c. 348 BCE)

A *Platonic solid* is a convex multifaceted 3-D object whose faces are all identical polygons, with sides of equal length and angles of equal degrees. A Platonic solid also has the same number of faces meeting at every vertex. The best-known example of a Platonic solid is the cube, whose faces are six identical squares.

The ancient Greeks recognized and proved that only five Platonic solids can be constructed: the tetrahedron, cube, octahedron, dodecahedron, and icosahedron. For example, the icosahedron has 20 faces, all in the shape of equilateral triangles.

Plato described the five Platonic solids in *Timaeus* in around 350 BCE. He was not only awestruck by their beauty and symmetry, but he also believed that the shapes described the structures of the four basic elements thought to compose the cosmos. In particular, the tetrahedron was the shape that represented fire, perhaps because of the polyhedron's sharp edges. The octahedron was air. Water was made up of icosahedra, which are smoother than the other Platonic solids. Earth consisted of cubes, which look sturdy and solid. Plato decided that God used the dodecahedron for arranging the constellations in the heavens.

Pythagoras of Samos—the famous mathematician and mystic who lived in the time of Buddha and Confucius, around 550 BCE—probably knew of three of the five Platonic solids (the cube, tetrahedron, and dodecahedron). Slightly rounded versions of the Platonic solids made of stone have been discovered in areas inhabited by the late Neolithic people of Scotland at least 1,000 years before Plato. The German astronomer Johannes Kepler (1571–

1630) constructed models of Platonic solids nested within one another in an attempt to describe the orbits of the planets about the sun. Although Kepler's theories were wrong, he was one of the first scientists to insist on a geometrical explanation for celestial phenomena.

SEE ALSO Pythagorean Theorem and Triangles (c. 600 BCE), Euclid's *Elements* (c. 300 BCE), Tesseract (1888).

A traditional dodecahedron is a polyhedron with 12 pentagonal faces. Shown here is Paul Nylander's graphical approximation of a hyperbolic dodecahedron, which uses a portion of a sphere for each face.

c. 300 BCE

Euclid's *Elements* • *Clifford A. Pickover*

Euclid of Alexandria (c. 325 BCE–c. 270 BCE)

The geometer Euclid of Alexandria lived in Hellenistic Egypt, and his book *Elements* is one of the most successful textbooks in the history of mathematics. His presentation of plane geometry is based on theorems that can all be derived from just five simple axioms, or postulates, one of which is that only one straight line can be drawn between any two points. Given a point and a line, another famous postulate suggests that only one line through the point is parallel to the first line. In the 1800s, mathematicians finally explored Non-Euclidean Geometries, in which the parallel postulate was no longer always required. Euclid's methodical approach of proving mathematical theorems by logical reasoning not only laid the foundations of geometry but also shaped countless other areas concerning logic and mathematical proofs.

Elements consists of 13 books that cover two- and three-dimensional geometries, proportions, and the theory of numbers. *Elements* was one of the first books to be printed after the invention of the printing press and was used for centuries as part of university curricula. More than 1,000 editions of *Elements* have been published since its original printing in 1482. Although Euclid was probably not the first to prove the various results in *Elements,* his clear organization and style made the work of lasting significance. Mathematical historian Thomas Heath called *Elements* "the greatest mathematical textbook of all time." Scientists like Galileo Galilei and Isaac Newton were strongly influenced by *Elements*. Philosopher and logician Bertrand Russell wrote, "At the age of eleven, I began Euclid, with my brother as my tutor. This was one of the great events of my life, as dazzling as first love. I had not imagined that there was anything so delicious in the world.” The poet Edna St. Vincent Millay wrote, “Euclid alone has looked on Beauty bare.”

SEE ALSO Pythagorean Theorem and Triangles (c. 600 BCE), Aristotle’s *Organon* (c. 350 BCE), Descartes’ *La Géométrie* (1637), Non-Euclidean Geometry (1829).

This is the frontispiece of Adelard of Bath’s translation of Euclid’s Elements, c. 1310. This translation from Arabic to Latin is the oldest surviving Latin translation of Elements.

c. 250 BCE

Archimedes’ Principle of Buoyancy •

Clifford A. Pickover

Archimedes (c. 287 BCE–c. 212 BCE)

Imagine that you are weighing an object—like a fresh, uncooked egg—that is submerged in a kitchen sink. If you weigh the egg by hanging it from a scale, the egg would weigh less while in the water, according to the scale, than when the egg is lifted out of the sink and weighed. The water exerts an upward force that partially supports the weight of the egg. This force is more obvious if we perform the same experiment with an object of lower density, such as a cube made out of cork, which floats while being partially submerged in the water.

The force exerted by the water on the cork is called a buoyant force, and for a cork held under water, the upward force is greater than its weight. This buoyant force depends on the density of the liquid and the volume of the object, but not on the shape of the object or the material of which the object is composed. Thus, in our experiment, it doesn’t matter if the egg is shaped like a sphere or a cube. An equal volume of egg or wood would experience the same buoyant force in water.

According to Archimedes’ Principle of Buoyancy, named after the Greek mathematician and inventor famous for his geometric and hydrostatic studies, a body wholly or partially submerged in liquid is buoyed up by a force equal to the weight of displaced liquid.

As another example, consider a small pellet of lead placed in a bathtub. The pellet weighs more than the tiny weight of water it displaces, so the pellet sinks. A wooden rowboat is buoyed up by the large weight of water that it displaces, and hence the rowboat floats. A submarine floating underwater displaces a volume of water that has a weight that is precisely equal to the submarine's weight. In other words, the total weight of the submarine—which includes the people, the metal hull, and the enclosed air—equals the weight of displaced seawater.

SEE ALSO Acceleration of Falling Objects (1638), Newton's Laws of Motion and Gravitation (1687), Bernoulli's Law of Fluid Dynamics (1738).

When plesiosaurs (extinct reptiles) floated within the sea, their total weights equaled the weights of the water they displaced. Gastrolith stones discovered in the stomach region of plesiosaur skeletons may have helped in controlling buoyancy and flotation.

c. 250 BCE

π • *Clifford A. Pickover*

Archimedes of Syracuse (c. 287 BCE–c. 212 BCE)

Pi, symbolized by the Greek letter π, is the ratio of a circle's circumference to its diameter and is approximately equal to 3.14159. Perhaps ancient peoples observed that for every revolution of a cartwheel, a cart moves forward about three times the diameter of the wheel—an early recognition that the circumference is about three times the diameter. An ancient Babylonian tablet states that the ratio of the circumference of a circle to the perimeter of an inscribed hexagon is 1 to 0.96, implying a value of pi of 3.125. Greek mathematician Archimedes (c. 250 BCE) was the first to give us a mathematically rigorous range for π—a value between 223/71 and 22/7. The Welsh mathematician William Jones (1675–1749) introduced the symbol π in 1706, most likely after the Greek word for periphery, which starts with the letter π.

The most famous ratio in mathematics is π, on Earth and probably for any advanced civilization in the universe. The digits of π never end, nor has anyone detected an orderly pattern in their arrangement. The speed with which a computer can compute π is an interesting measure of a computer's computational ability, and today we know more than a trillion digits of π.

We usually associate π with a circle, and so did pre-seventeenth-century humanity. However, in the seventeenth century, π was freed from the circle. Many curves were invented and studied (for example, various arches, hypocycloids, and curves known as *witches*), and it was found that their areas could be expressed in terms of π. Finally, π appeared to flee geometry altogether, and today π relates to unaccountably many areas in number theory, probability, complex numbers, and series of simple fractions, such as

$\pi/4 = 1 - 1/3 + 1/5 - 1/7. . .$ In 2006, Akira Haraguchi, a retired Japanese engineer, set a world record for memorizing and reciting 100,000 digits of π.

SEE ALSO Golden Ratio (1509), Euler's Number, *e* (1727), Transcendental Numbers (1844).

Pi is approximately equal to 3.14 and is the ratio of a circle's circumference to its diameter. Ancient peoples may have noticed that for every revolution of a cart wheel, the cart moves forward about three times the diameter of the wheel.

c. 240 BCE

Eratosthenes Measures the Earth •

Clifford A. Pickover

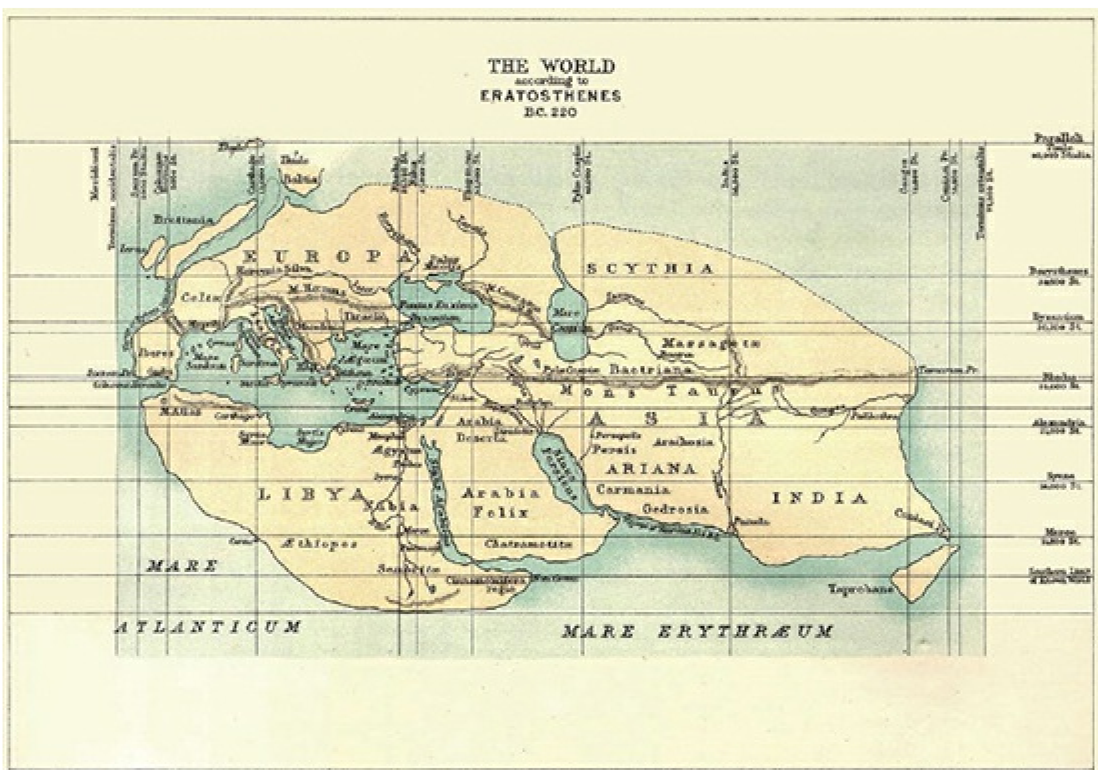
Eratosthenes of Cyrene (c. 276 BCE–c. 194 BCE)

According to author Douglas Hubbard, "Our first mentor of measurement did something that was probably thought by many in his day to be impossible. An ancient Greek named Eratosthenes made the first recorded measurement of the circumference of Earth. . . . [He] didn't use accurate survey equipment, and he certainly didn't have lasers and satellites. . . ." However, Eratosthenes knew of a particular deep well in Syene, a city in southern Egypt. The bottom of this well was entirely lit by the noon Sun one day out of the year, and thus the sun was directly overhead. He also was aware that, at the same time in the city of Alexandria, objects cast a shadow, which suggested to Eratosthenes that the Earth was spherical, not flat. He assumed that the Sun's rays were essentially parallel, and he knew that the shadow made an angle that was 1/50th of a circle. Thus, he determined that the circumference of the Earth must be approximately 50 times the known distance between Alexandria and Syene. Assessments of Eratosthenes' accuracy vary, due to the conversion of his ancient units of measure to modern units, along with other factors, but his measurements are usually deemed to be within a few percent of the actual circumference. Certainly, his estimation was more accurate than other estimates of his day. Today, we know that the circumference of the Earth at the equator is about 24,900 miles (40,075 kilometers). Curiously, if Columbus had not ignored the results of Eratosthenes, thereby underestimating the circumference of the Earth, the goal of reaching Asia by sailing west might have been considered to be an impossible task.

Eratosthenes was born in Cyrene (now in Libya) and later was a director of the great Library of Alexandria. He is also famous for founding scientific chronology (a system that endeavors to fix dates of events at correctly proportioned intervals), along with developing a simple algorithm for identifying prime numbers (numbers such as 13, divisible only by themselves and 1). In old age, Eratosthenes became blind and starved himself to death.

SEE ALSO Sundial (c. 3000 BCE) Telescope (1608), Measuring the Solar System (1672).

Eratosthenes' map of the world (1895 reconstruction). Eratosthenes measured the circumference of the Earth without leaving Egypt. Ancient and medieval European scholars often believed that the world was spherical, although they were not aware of the Americas.



c. 240 BCE

Sieve of Eratosthenes • *Clifford A. Pickover*

Eratosthenes (c. 276 BCE–c. 194 BCE)

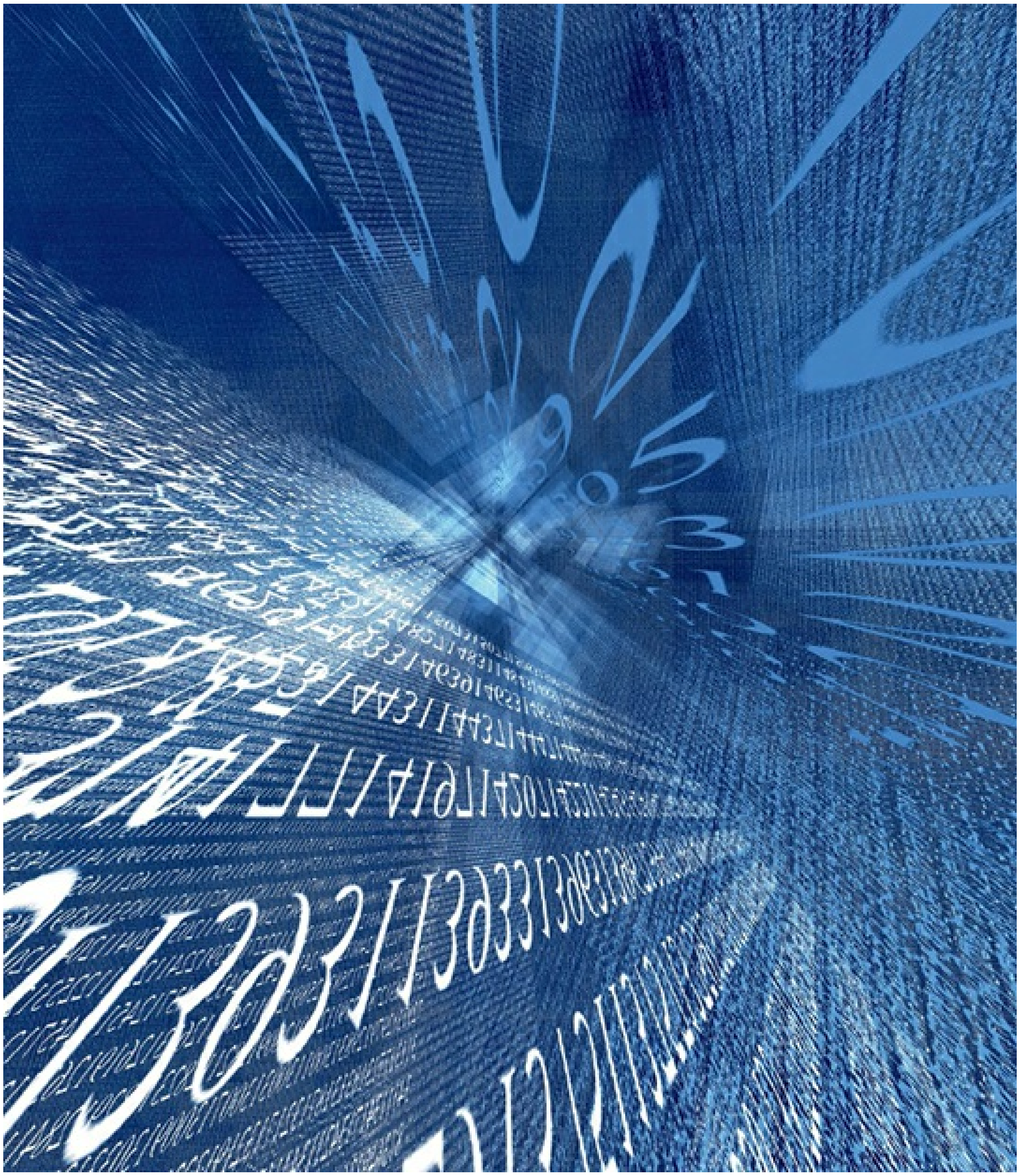
A prime number is a number larger than 1, such as 5 or 13, that is divisible only by itself or 1. The number 14 is not prime because 14 = 7 × 2. Prime numbers have fascinated mathematicians for more than two thousand years. Around 300 BCE, Euclid showed that there is no "largest prime" and that an infinitude of prime numbers exists. But how can we determine if a number is prime? Around 240 BCE, the Greek mathematician Eratosthenes developed the first-known test for primality, which we today call the Sieve of Eratosthenes. In particular, the Sieve can be used to find all prime numbers up to a specified integer. (The ever-versatile Eratosthenes served as the director of the famous library in Alexandria and was also the first person to provide a reasonable estimation of the diameter of the Earth.)

The French theologian and mathematician Marin Mersenne (1588–1648) was also fascinated by prime numbers, and he tried to find a formula that he could use to find all primes. Although he did not find such a formula, his work on Mersenne numbers of the form $2^p - 1$, where p is an integer, continues to be of interest to us today. Mersenne numbers, with p a prime number, are the easiest type of number to prove prime, so they are usually the largest primes of which humanity is aware. The forty-fifth known Mersenne prime ($2^{43,112,609} - 1$) was discovered in 2008, and it contains 12,978,189 digits!

Today, prime numbers play an important role in public-key cryptography algorithms that may be used for sending secure messages. More important, for pure mathematicians, prime numbers have been at the heart of many intriguing unsolved conjectures through history, including the Riemann Hypothesis, which concerns the distribution of prime numbers, and the strong Goldbach Conjecture, which states that every even integer greater than 2 can be written as a sum of two primes.

SEE ALSO Ishango Bone (c. 18,000 BCE) Riemann Hypothesis (1859), Proof of the Prime Number Theorem (1896), Public-Key Cryptography (1977).

Polish artist Andreas Guskos creates contemporary art by concatenating thousands of prime numbers and using them as textures on various surfaces. This work is called Eratosthenes, after the Greek mathematician who developed the first-known test for primality.



c. 230 BCE

Pulley • *Clifford A. Pickover*

Archimedes (c. 287 BCE–c. 212 BCE)

A pulley is a mechanism that usually consists of a wheel on an axle. A rope runs over the wheel so that the pulley can change the direction of an applied force, for example, when helping a human or a machine lift or pull heavy loads. The pulley also makes it easier to move a load because it decreases the applied force needed.

The pulley probably had its birth in prehistoric times when someone tossed a rope over a horizontal tree branch and used it to lift a heavy object. Author Kendall Haven writes, "By 3000 BCE, such pulleys with grooved wheels (so that the rope wouldn't slip off) existed in Egypt and Syria. The Greek mathematician and inventor Archimedes gets credit for inventing the *compound* pulley in about 230 BCE . . . in which a number of wheels and ropes combine to lift a single object . . . to multiply the lifting power of a person. Modern block and tackle systems are examples of compound pulleys."

Pulleys almost seem magical in the way they can decrease the width and strength of the rope required, and of the force needed, to lift heavy objects. In fact, according to legends and the writings of the Greek historian Plutarch, Archimedes may have used a compound pulley to help move heavy ships with minimal effort. Of course, no laws of nature are violated. Work, which is defined as force times the distance moved, remains the same—pulleys allow one to pull with less force but over a longer distance. In practice, more pulleys increase the sliding friction, and, thus, a system of pulleys may become decreasingly efficient after a certain number are employed. When performing computations to estimate the effort needed to use a pulley system, engineers often assume that the pulley and rope weigh very little compared to the weight that is being moved. Through history, block-and-tackle systems were particularly common on sailing ships, where motorized aids were not always available.

SEE ALSO Gears (c. 50), Acceleration of Falling Objects (1638), Newton's Laws of Motion and Gravitation (1687).

Close-up of a pulley system on a vintage yacht. Ropes in pulleys travel over wheels so that the pulley can change the direction of applied forces and make it easier to move a load.

c. 125 BCE

Antikythera Mechanism • *Clifford A. Pickover*

Valerios Stais (1857–1923)

The Antikythera mechanism is an ancient geared computing device that was used to calculate astronomical positions and that mystified scientists for over a century. Discovered around 1902 by archaeologist Valerios Stais in a shipwreck off the coast of the Greek island Antikythera, the device is thought to have been built about 150–100 BCE. Journalist Jo Marchant writes, “Among the salvaged hoard subsequently shipped to Athens was a piece of formless rock that no one noticed at first, until it cracked open, revealing bronze gearwheels, pointers, and tiny Greek inscriptions. . . . A sophisticated piece of machinery consisting of precisely cut dials, pointers and at least thirty interlocking gear wheels, nothing close to its complexity appears again in the historical record for more than a thousand years, until the development of astronomical clocks in medieval Europe.”

A dial on the front of the device probably carried at least three hands, one indicating the date and the other two indicating the positions of the Sun and the Moon. The device was also probably used to track dates of ancient Olympic games, predict solar eclipses, and indicate other planetary motions.

Of special delight to physicists, the Moon mechanism uses a special train of bronze gears, two of them linked with a slightly offset axis, to indicate the position and phase of the moon. As is known today from Kepler’s Laws of Planetary Motion, the moon travels at different speeds as it orbits the Earth (e.g. faster when it is closer to the Earth), and this speed differential is modeled by the Antikythera mechanism, even though the ancient Greeks were not aware of the actual elliptical shape of the orbit. Additionally, the Earth travels faster when it is closer to the Sun than when it is far away.

Marchant writes, “By turning the handle on the box you could make time pass forwards or backwards, to see the state of the cosmos today, tomorrow, last Tuesday or a hundred years in the future. Whoever owned this device must have felt like master of the heavens.”

SEE ALSO Kepler’s Laws of Planetary Motion (1609), Slide Rule (1621), ENIAC (1946)

The Antikythera mechanism is an ancient geared computing device that was used to calculate astronomical positions. X-ray radiographs of the mechanism have revealed information about the device’s internal configuration. (Photo courtesy of Rien van de Weijgaert.)

c. 50

Gears • *Clifford A. Pickover*

Hero (or Heron) of Alexandria (c. 10–c. 70 A.D.)

Rotating gears, with their intermeshed teeth, have played a crucial role in the history of technology. Not only are gear mechanisms important for increasing the applied twisting force, or torque, but gears are also useful for changing the speed and direction of force. One of the oldest machines is a potter's wheel, and primitive gears associated with these kinds of wheels probably existed for thousands of years. In the fourth century BCE, Aristotle wrote about wheels using friction between smooth surfaces to convey motions. Built around 125 BCE, the Antikythera Mechanism employed toothed gears for calculating astronomical positions. One of the earliest written references to toothed gears was made by Hero of Alexandria, c. 50 A.D. Through time, gears have played a crucial role in mills, clocks, bicycles, cars, washing machines, and drills. Because they are so useful in amplifying forces, early engineers used them for lifting heavy construction loads. The speed-changing properties of gear assemblies were put to use when ancient textile machines were powered by the movement of horses or water. The rotational speed of these power supplies was often insufficient, so a set of wooden gears was used to increase the speed for textile production.

When two gears are intermeshed, the rotational speed ratio s_1/s_2 is simply the reciprocal ratio of the number n of teeth on the two gears: $s_1/s_2 = n_2/n_1$. Thus, a small gear turns faster than its larger partner. The torque ratio has an opposite relationship. The larger gear experiences greater torque, and the higher torque implies lower velocity. This is useful, for example, for electric screwdrivers, in which the motor can produce a small amount of torque at high speed, but we wish to have a slow *output* speed with increased torque.

Among the simplest gears are *spur gears*, with their straight-cut teeth. *Helical gears* in which the teeth are set at an angle have the advantage of running more smoothly and quietly and usually being able to handle greater torques.

SEE ALSO Pulley (c. 230 BCE) Conservation of Energy (1843), Steam Turbine (1890).

Gears have played important roles in history. Gear mechanisms can increase the applied force or torque and are also useful for changing the speed and direction of a force.

c. 126

Roman Concrete • *Derek B. Lowe*

Pliny the Elder (23−79)

Concrete is everywhere in our civilization; modern construction wouldn't be possible without it. But its chemistry is surprisingly complex, depending on two elements (aluminum and silicon) that form strong bonding networks with oxygen atoms. These species, which are abundant in Earth's crust, form the basis for a huge variety of minerals and man-made ceramics. Concrete also requires calcium ions and a reaction with water to help hold everything together, but the technical name, hydrated calcium aluminosilicate, although an accurate description of concrete's chemical composition, doesn't roll off the tongue very easily.

The Romans had the finest concrete of the ancient world, and some of it can still be seen today in such magnificent structures as the famous Pantheon—completed around the year 126 and still the largest unreinforced concrete dome in the world. Roman civilization, though, was actually "science deficient"; considering their power and longevity, surprisingly little basic research was done. They didn't have much patience for mathematics, blue-sky experimentation, or abstract theories, but practical improvements in civil and military engineering were always welcome. As such, the Romans developed a variety of concrete mixtures for different applications. Their water-resistant mix was of very high quality, and according to the natural philosopher Pliny the Elder, a key ingredient in the mortar was the ashy volcanic deposits (now known as pozzolan) from the area of Mount Vesuvius. Pliny knew the area well—too well, in the end, since he was killed in the famous 79 eruption that destroyed Pompeii.

Just in the last few years, analytical chemists have been able to work out how this recipe for Roman maritime concrete must have been made. The process requires quite a bit less energy than modern Portland cement, which was developed in nineteenth-century Britain. In terms of the fuel needed to bake the starting limestone mix, the time needed to cure the finished product, and its durability in salt water, the Roman recipe has many advantages. After almost two thousand years, it may be making a comeback.

SEE ALSO Bronze (c. 3300 BCE), Arch (c. 1850 BCE) Polyethylene (1933), Rubber (1839).

The two-thousand-year-old Pantheon in Rome still has the largest unreinforced concrete dome in the world—a solid testament to Roman engineering.

c. 650

Zero • *Clifford A. Pickover*

Brahmagupta (c. 598–c. 668), **Bhaskara** (c. 600–c. 680), **Mahavira** (c. 800–c. 870)

The ancient Babylonians originally had no symbol for zero, which caused uncertainty in their notation, just as today we would be confused if numbers like 12, 102, and 1,002 had no zero to distinguish them. The Babylonian scribes only left a space where a zero should be, and it was not easy to distinguish the number of spaces in the middle or at the ends of numbers. Eventually, the Babylonians did invent a symbol to mark the gap between their digits, but they probably had no concept of zero as an actual number.

Around A.D. 650, the use of the number was common in Indian mathematics, and a stone tablet was found in Gwalior, south of Delhi, with the numbers 270 and 50. The numbers on the tablet, dated to A.D. 876, look very similar to modern numbers, except that the zeros are smaller and raised. Indian mathematicians such as Brahmagupta, Mahavira, and Bhaskara used zero in mathematical operations. For example, Brahmagupta explained that a number subtracted from itself gives zero, and he noted that any number when multiplied by zero is zero. The Bakhshali Manuscript may be the first documented evidence of zero used for mathematical purposes, but its date is unclear.

Around A.D. 665, the Mayan civilization in Central America also developed the number zero, but its achievement did not seem to influence other peoples. On the other hand, the Indian concept of zero spread to the Arabs, Europeans, and Chinese, and changed the world.

Mathematician Hossein Arsham writes, “The introduction of zero into the decimal system in the thirteenth century was the most significant achievement in the development of a number system, in which calculation with large numbers became feasible. Without the notion of zero, the . . . modeling processes in commerce, astronomy, physics, chemistry, and industry would have been unthinkable. The lack of such a symbol is one of the serious drawbacks in the Roman numeral system."

SEE ALSO Rhind Papyrus (c. 1650 BCE), al-Khwarizmi's *Algebra* (830), Fibonacci's *Liber Abaci* (1202).

The notion of zero ignited a fire that eventually allowed humanity to more easily work with large numbers and to become efficient in calculations in fields ranging from commerce to physics.

830

Al-Khwarizmi's *Algebra* • *Clifford A. Pickover*

Abu Ja'far Muhammad ibn Musa al-Khwarizmi (c. 780–c. 850)

Al-Khwarizmi was a Persian mathematician and astronomer who spent most of his life in Baghdad. His book on algebra, *Kitab al-mukhtasar fi hisab al-jabr wa'l-muqabala* (*The Compendious Book on Calculation by Completion and Balancing*), was the first book on the systematic solution of linear and quadratic equations and is sometimes referred to by the shortened title *Algebra*. Along with Diophantus, he is considered the "father of algebra." The Latin translation of his works introduced the decimal positional number system to Europe. Interestingly, the word *algebra* comes from *al-jabr*, one of the two operations used in his book to solve quadratic equations.

For al-Khwarizmi, al-jabr is a method in which we can eliminate negative quantities in an equation by adding the same quantity to each side. For example, we can reduce $x^2 = 50x - 5x^2$ to $6x^2 = 50x$ by adding $5x^2$ to both sides. *Al-muqabala* is a method whereby we gather quantities of the same type to the same side of the equation. For example, $x^2 + 15 = x + 5$ is reduced to $x^2 + 10 = x$.

The book helped readers to solve equations such as those of the forms $x^2 + 10x = 39$, $x^2 + 21 = 10x$, and $3x + 4 = x^2$, but more generally, al-Khwarizmi believed that the difficult mathematical problems could be solved if broken down into a series of smaller steps. Al-Khwarizmi intended his book to be practical, helping people to make calculations that deal with money, property inheritance, lawsuits, trade, and the digging of canals. His book also contained example problems and solutions.

Al-Khwarizmi worked most of his life in the Baghdad House of Wisdom, a library, translation institute, and place of learning that was a major intellectual center of the Islamic Golden Age. Alas, the Mongols destroyed the House of Wisdom in 1258, and legend says that the waters of the Tigris ran black with ink from the books tossed into its waters.

SEE ALSO Fibonacci's *Liber Abaci* (1202), Development of Modern Calculus (1665), Fundamental Theorem of Algebra (1797).

A stamp from the Soviet Union, issued in 1983 in honor of al-Khwarizmi, the Persian mathematician and astronomer whose book on algebra offered a systematic solution to a wide variety of equations.


ПОЧТА СССР
1983
4к
1200 ЛЕТ
Мухаммед
аль-Хорезми

c. 850

Gunpowder • *Derek B. Lowe*

Gunpowder probably was discovered by alchemists trying to transmute metals or extend life rather than by weapons engineers seeking an explosive. A Chinese military compendium from 1044 listed a number of different recipes for gunpowder, showing that it had been the subject of a lot of action-packed research and development by the middle of the Song dynasty, but the first known mention comes from a mid-ninth-century Taoist text, which stressed its dangerously flammable nature. Sulfur was of great importance in alchemy, and any lab of the time would have had charcoal around for fuel. The third key ingredient—the oxidizer potassium nitrate—was available as the naturally occurring mineral niter (also known as saltpeter) or as crystals around deposits of bat guano in caves. Whoever first combined these powders and exposed the resulting mixture to a flame must have immediately realized that they were onto something big. Extending human life, though, turned out not to be gunpowder's strong point.

Knowledge of the new weapon diffused through China and past its borders, and the Mongol invasions of the thirteenth century spread the news even farther, from India to Europe. The Chinese kept raising the amount of potassium nitrate in their gunpowder as time went on, producing bigger explosions all the time. Early artillery shells, exploding arrows, and a variety of alarming bomb designs show up in several Chinese military manuscripts. In his Treatise on Horsemanship and Stratagems of War (c. 1280), detailing 107 different explosive mixtures, Syrian chemist Hasan al-Rammah referred to potassium nitrate as "Chinese snow." European militaries adopted gunpowder quickly: the first illustration of a firearm—a primitive metal cannon known as a pot-de-fer (French for "iron pot") with an enormous arrow emerging from its barrel—appeared in a 1326 manuscript by the English scholar Walter de Milemete. For better or worse, it has been with us ever since.

SEE ALSO Iron Smelting (c. 1300 BCE) Internal Combustion Engine (1908), Little Boy Atomic Bomb (1945).

An explosion of gunpowder shells during the 1274 Mongol invasion of Japan, illustrated in a scroll commissioned some twenty years after the battle.

1202

Fibonacci's *Liber Abaci* • *Clifford A. Pickover*

Leonardo of Pisa (also known as Fibonacci, c. 1175–c. 1250)

Carl Boyer refers to Leonardo of Pisa, also known as Fibonacci, as "without a doubt, the most original and most capable mathematician of the medieval Christian world." Fibonacci, a wealthy Italian merchant, traveled through Egypt, Syria, and Barbary (Algeria), and in 1202 published the book *Liber Abaci* (*The Book of the Abacus*), which introduced the Hindu-Arabic numerals and decimal number system to Western Europe. This system is now used throughout the world, having overcome the terribly cumbersome Roman numerals common in Fibonacci's time. In *Liber Abaci*, Fibonacci notes, "These are the nine figures of the Indians: 9 8 7 6 5 4 3 2 1. With these nine figures, and with this sign 0, which in Arabic is called *zephirum*, any number can be represented, as will be demonstrated."

Although *Liber Abaci* was not the first European book to describe the Hindu-Arabic numerals—and even though decimal numerals did not gain widespread use in Europe directly after its publication—the book is nevertheless considered to have had a strong impact on European thought because it was directed to both academicians and businesspeople.

Liber Abaci also introduced Western Europe to the famous number sequence 1, 1, 2, 3, 5, 8, 13. . ., which today is called the *Fibonacci sequence*. Notice that except for the first two numbers, every successive number in the sequence equals the sum of the previous two. These numbers appear in an amazing number of mathematical disciplines and in nature.

Is God a mathematician? Certainly, the universe seems to be reliably understood using mathematics. Nature *is* mathematics. The arrangement of seeds in a sunflower can be understood using Fibonacci numbers. Sunflower heads, like those of other flowers, contain families of interlaced spirals of seeds—one spiral winding clockwise, the other counterclockwise. The number of spirals in such heads, as well as the number of petals in flowers, is very often a Fibonacci number.

SEE ALSO Zero (c. 650), Golden Ratio (1509), Pascal's Triangle (1654)

Sunflower heads contain families of interlaced spirals of seeds—one spiral winding clockwise, the other counterclockwise. The number of spirals in such heads, as well as the number of petals in flowers, is very often a Fibonacci number.

1284

Eyeglasses • *Clifford A. Pickover*

Salvino D'Armate of Florence (1258–1312), **Giambattista della Porta** (1535–1615), **Edward Scarlett** (1677–1743)

Historian Lois N. Magner writes, "The use of spectacles must have occasioned a profound effect on attitudes towards human limitations and liabilities. Spectacles not only made it possible for scholars and copyists to continue their work, they accustomed people to the idea that certain physical limitations could be transcended by the use of human inventions."

Today, the terms *eyeglasses* and *spectacles* usually refer to lenses attached to a frame to correct vision problems. Various forms have existed through history, including the pince-nez (supported only by pinching the bridge of the nose, with no earpieces), monocle (a circular lens over one eye), and lorgnette (spectacles with a handle).

By 1000 A.D., "reading stones"—crystals or segments of a glass sphere placed on reading material to magnify the text—were common. Eyeglasses were in use in China by the time of Marco Polo's journey, around 1270, and they may have been used in Arabia even earlier. In 1284, the Italian Salvino D'Armate became perhaps the most famous inventor of eyeglasses in Europe. The earliest eyeglasses made use of convex glasses for the correction of hyperopia (farsightedness) and presbyopia (age-related farsightedness). One early reference to concave lenses for nearsightedness (also called myopia, in which distant objects appear blurred and near objects are clear) occurred in *Natural Magick* (1558), by Italian scholar Giambattista della Porta. Convex lenses were used to see text that was close to the eye.

Spectacles were once so expensive that they were listed in wills as valuable property. Around 1727, British optician Edward Scarlett developed the modern style of glasses, held by rigid arms that hook over the ears. The American scientist Benjamin Franklin invented bifocals in 1784 to address his combination of myopia and presbyopia.

Today, many eyeglasses are made of the plastic CR-39 due to its favorable optical properties and durability. Lenses are generally used to change the focus location of light rays so that they properly intersect the retina, the light-sensitive tissue at the back of the eye.

SEE ALSO Telescope (1608), *Micrographia* (1665), Laser (1960).

A lorgnette is a pair of spectacles with a handle. It was invented in the 1700s by English optical designer George Adams. Some owners did not need glasses to see better, but carried ornate lorgnettes to be fashionable.

c. 1500

Early Calculus • *Jim Bell*

Ma¯dhavan of Sangamagra¯mam (c. 1350–c.1425), **Nı¯lakantha Soma¯yaji** (1444–1544)

Astronomical research in India through the Middle Ages was initially based on the early findings and writings of Aryabhata and other mathematicians and astronomers; it was ultimately expanded by the creation of dedicated research and teaching groups like the Kerala school of astronomy and mathematics, founded in the fourteenth century by the mathematician Ma¯dhavan of Sangamagra¯mam.

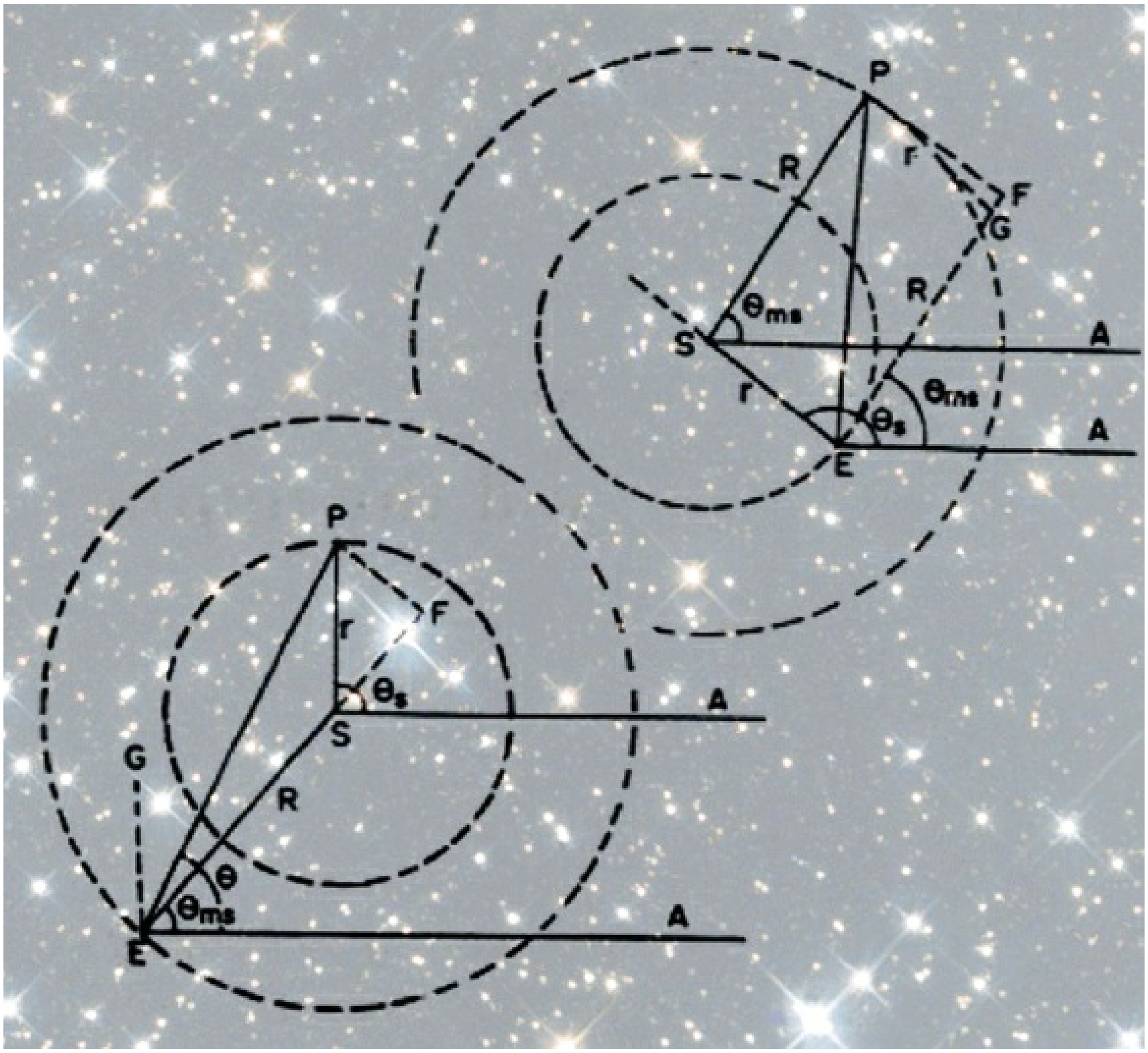
Ma¯dhavan and subsequent Kerala mathematicians like Nı¯lakantha Soma¯yaji developed mathematical methods of estimating the motions of the planets based initially on geometry and trigonometry and later on newly developed techniques for modeling complex curves and mathematical shapes using combinations of functions. Among these shapes were parabolas, hyperbolas, and ellipses; their work on ellipses proved especially applicable to astronomy because they were able to show that Aryabhata's earlier conjecture was correct: the paths of the planets could be described by elliptical orbits. The new mathematical methods developed at Kerala that focused on series of functions were early versions of calculus, predating the European development of calculus some 200 years later by scientists like Isaac Newton.

Nı¯lakantha's work *Aryabhatiyabhasya* (a commentary on Aryabhata's *Aryabhatiya*), published around 1500, further demonstrated that a rotating Earth and a partially heliocentric solar system provided a more accurate way of fitting the planetary orbits. In his model, Mercury, Venus, Mars, Jupiter, and Saturn all orbited the Sun, but the Sun orbited Earth. A similar model was adopted by the sixteenth-century Danish astronomer Tycho Brahe, and some aspects of Nı¯lakantha's model are also consistent with the fully heliocentric cosmology proposed in 1543 by Polish astronomer Nicolaus Copernicus.

The contributions of the Kerala school, and perhaps of Indian mathematics and astronomy in general, may have previously been underappreciated in the West. It seems clear now that they should be counted among the "shoulders of giants" that supported the later discoveries of Copernicus, Newton, and others.

SEE ALSO Sun-Centered Universe (1534), Kepler's Laws of Planetary Motion (1609), Development of Modern Calculus (1665).

Planetary orbital calculations by mathematicians from the Kerala school in southern India, active between the fourteenth and sixteenth centuries, fit a heliocentric model for the solar system. This figure shows some examples from modern Indian physicists reconstructing the geometry used by Kerala school astronomers.


P
R
r
F
G
R
θ_{ms}
S
A
r
θ_s
θ_{ms}
A
E
P
r
F
θ_s
A
S
G
R
θ
θ_{ms}
A
E

1509

Golden Ratio • *Clifford A. Pickover*

Fra Luca Bartolomeo de Pacioli (1445–1517)

In 1509, Italian mathematician Luca Pacioli, a close friend of Leonardo da Vinci, published *Divina Proportione*, a treatise on a number that is now widely known as the "Golden Ratio." This ratio, symbolized by ø, appears with amazing frequency in mathematics and nature. We can understand the proportion most easily by dividing a line into two segments so that the ratio of the whole segment to the longer part is the same as the ratio of the longer part to the shorter part, or $(a + b)/b = b/a = 1.61803...$

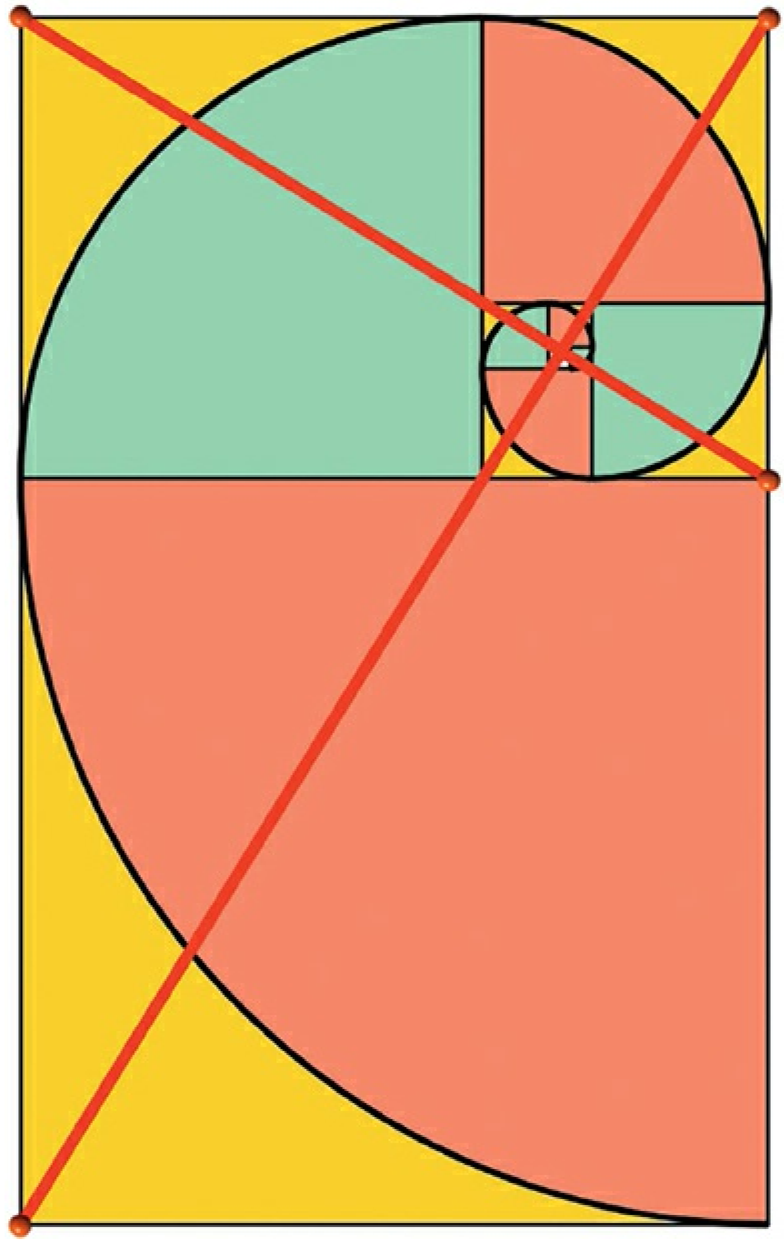
If the lengths of the sides of a rectangle are in the golden ratio, then the rectangle is a "golden rectangle." It's possible to divide a golden rectangle into a square and a golden rectangle. Next, we can cut the smaller golden rectangle into a smaller square and golden rectangle. We may continue this process indefinitely, producing smaller and smaller golden rectangles.

If we draw a diagonal from the top right of the original rectangle to the bottom left, and then from the bottom right of the baby (that is, the next smaller) golden rectangle to the top left, the intersection point shows the point to which all the baby golden rectangles converge. Moreover, the lengths of the diagonals are in golden ratio to each another. The point to which all the golden rectangles converge is sometimes called the "Eye of God."

The golden rectangle is the *only* rectangle from which a square can be cut so that the remaining rectangle will always be similar to the original rectangle. If we connect the vertices in the diagram, we approximate a logarithmic spiral that “envelops” the Eye of God. Logarithmic spirals are everywhere—seashells, animal horns, the cochlea of the ear—anywhere nature needs to fill space economically and regularly. A spiral is strong and uses a minimum of materials. While expanding, it alters its size but never its shape.

SEE ALSO Projective Geometry (1639), Euler’s Number, *e* (1727), Transcendental Numbers (1844).

Artistic depiction of golden ratios. Note that the two diagonal lines intersect at a point to which all the baby golden rectangles will converge.



1543

De Humani Corporis Fabrica • *Clifford A. Pickover*

Jan Stephan van Calcar (1499–1546), **Andreas Vesalius** (1514–1564)

“The publication of *De Humani Corporis Fabrica* [*On the Fabric of the Human Body*] of Andreas Vesalius in 1543 marks the beginning of modern science,” write medical historians J. B. de C. M. Saunders and Charles O’Malley. “It is without doubt the greatest single contribution to medical sciences, but it is a great deal more, an exquisite piece of creative art with its perfect blend of format, typography, and illustration.”

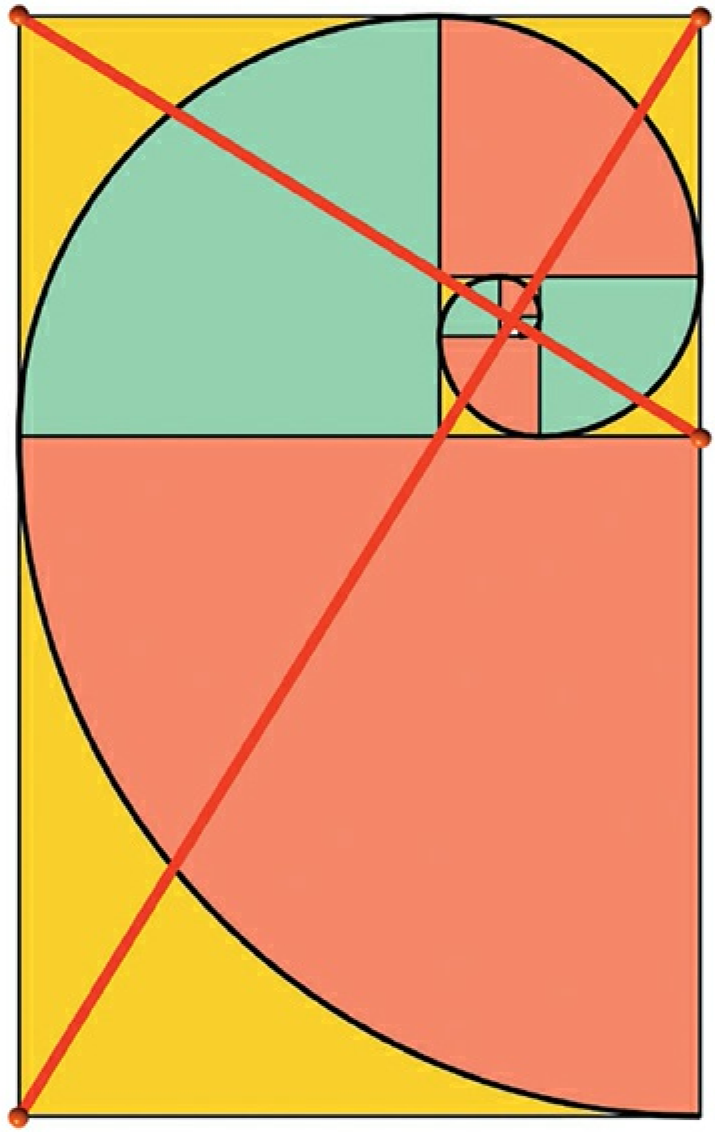
Physician and anatomist Andreas Vesalius of Brussels performed dissections as a primary teaching tool and showed that many previous ideas about the human body, from such great thinkers as Galen and Aristotle, were demonstrably incorrect. For example, in contradiction to Galen, Vesalius showed that blood did not pass from one side of the heart to the other through invisible pores. He also showed that the liver had two main lobes. His challenges to Galen made him the enemy of many, and a detractor even claimed that the human body must have *changed* since Galen’s studies to explain Vesalius’s observations! In actuality, Galen had based nearly all of his observations on animal dissections, which led to significant errors about humans.

As a medical student, Vesalius braved feral dogs and horrible stenches in his feverish attempts to obtain rotting corpses from cemeteries or the remains of executed criminals hanging from beams until they disintegrated. He even kept specimens in his bedroom for weeks while dissecting them.

Fabrica, Vesalius's groundbreaking anatomy book, was probably illustrated by Jan Stephan van Calcar or other pupils of the famous Italian painter Titian. The book revealed the inner structures of the brain as never before. Science journalist Robert Adler writes, "With the *Fabrica*, Vesalius effectively ended the slavish scholastic worship of the knowledge of the ancient world and demonstrated that a new generation of scientists could forge ahead and make discoveries the ancients never dreamed of. Along with a few other Renaissance giants such as Copernicus and Galileo, Vesalius created the progressive, science-driven world in which we live."

SEE ALSO Paré's "Rational Surgery" (1545), Circulatory System (1628), Morgagni's "Cries of Suffering Organs" (1761).

Delineation of spinal nerves from Vesalius's De Humani Corporis Fabrica.



1543

Sun-Centered Universe • *Clifford A. Pickover*

Nicolaus Copernicus (1473–1543)

"Of all discoveries and opinions," wrote the German polymath Johann Wolfgang von Goethe in 1808, "none may have exerted a greater effect on the human spirit than the doctrine of Copernicus. The world had scarcely become known as round and complete in itself when it was asked to waive the tremendous privilege of being the center of the universe. Never, perhaps, was a greater demand made on mankind—for by this admission so many things vanished in mist and smoke! What became of our Eden, our world of innocence, piety and poetry; the testimony of the senses; the conviction of a poetic-religious faith?"

Nicolaus Copernicus was the first individual to present a comprehensive heliocentric theory that suggested the Earth was not the center of the universe. His book, *De revolutionibus orbium coelestium* (*On the Revolutions of the Celestial Spheres*) was published in 1543, the year he died, and put forward the theory that the Earth revolved around the Sun. Copernicus was a Polish mathematician, physician, and classical scholar—astronomy was something he studied in his spare time—but it was in the field of astronomy that he changed the world. His theory relied on a number of assumptions: that the Earth's center is not the center of the universe, that the distance from the Earth to the Sun is miniscule when compared with the distance to the stars, that the rotation of the Earth accounts for the apparent daily rotation of the stars, and that the apparent retrograde motion of the planets (in which they appear to briefly stop and reverse directions at certain times when viewed from the Earth) is caused by the motion of the Earth. Although Copernicus' proposed circular orbits and epicycles of planets were incorrect, his work motivated other astronomers, such as Johannes Kepler, to investigate planetary orbits and later discover their elliptical nature.

Interestingly, it was not until many years later, in 1616, that the Roman Catholic Church proclaimed that Copernicus' heliocentric theory was false and "altogether opposed to Holy Scripture."

SEE ALSO Egyptian Astronomy (c. 2500 BCE) Telescope (1608), Kepler's Laws of Planetary Motion (1609), Measuring the Solar System (1672), Hubble Telescope (1990).

Orreries are mechanical devices that show positions and motions of the planets and moons in a heliocentric model of the solar system. Shown here is a device constructed in 1766 by instrument-maker Benjamin Martin (1704–1782) and used by astronomer John Winthrop (1714–1779) to teach astronomy at Harvard University. On display at the Putnam Gallery in the Harvard Science Center.

1545

Paré's "Rational Surgery" • *Clifford A. Pickover*

Ambroise Paré (1510–1590)

The French surgeon Ambroise Paré is one of the most celebrated surgeons of the European Renaissance. Surgeon and biographer Geoffrey Keynes writes, "Ambroise Paré was, by virtue of his personality and his independent mind, the emancipator of surgery from the dead hand of dogma. There was no comparable practitioner, during his time, in any other country, and his influence was felt in every part of Europe. He left in his collected 'Works' a monument to his own skill and humanity which is unsurpassed in the history of surgery." Paré's humble credo of patient care was "I dressed him, God cured him."

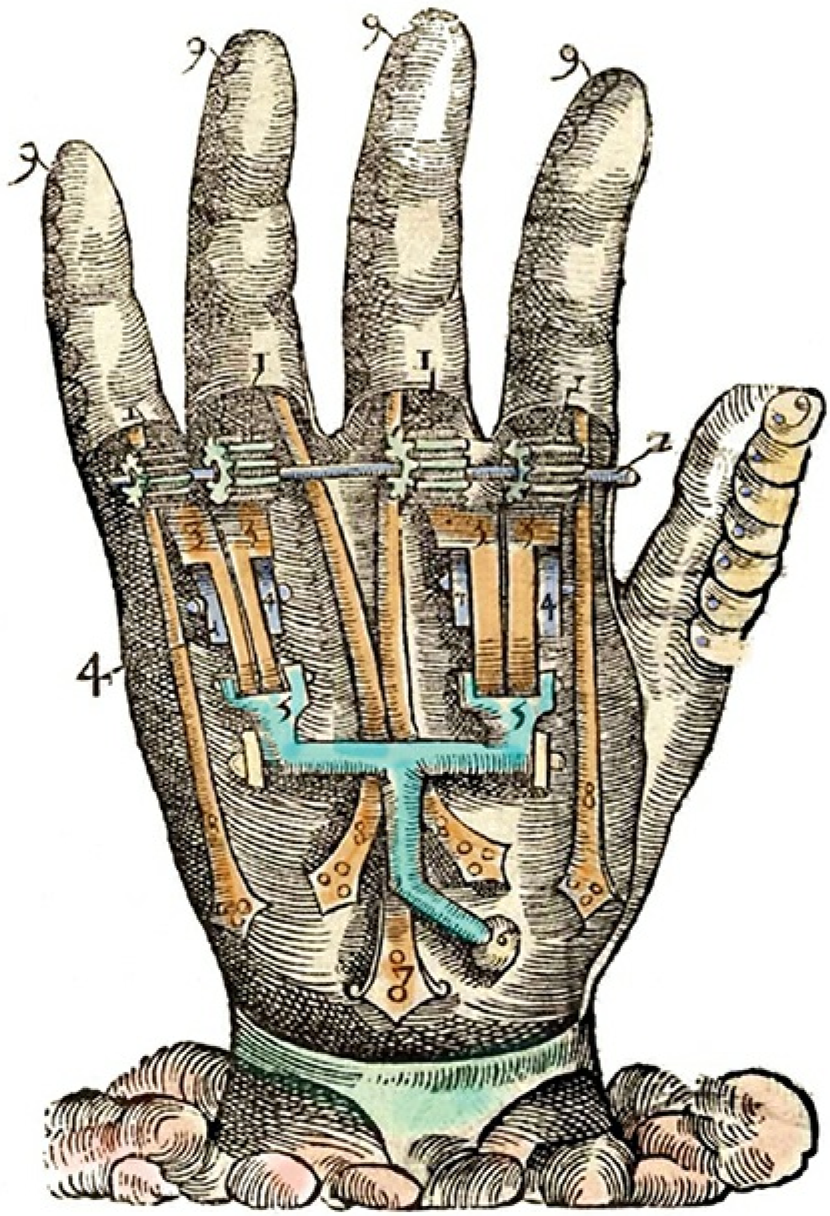
Paré lived during a time when physicians generally considered surgery beneath their dignity, and cutting of the body was left to the less prestigious "barber-surgeons." However, Paré elevated the status of surgeons and spread his surgical knowledge by writing in French rather than the traditional Latin.

Paré made his first significant medical discovery while treating gunshot wounds, which were considered to be poisonous and were usually dealt with by pouring boiling oil into the wound to burn it closed. One day, Paré ran out of oil and was forced to improvise with an ointment that contained turpentine. The next day, he discovered that the soldiers treated with boiling oil were in agony, with swollen wounds. However, the patients who had been treated with the more soothing ointment rested relatively comfortably with little signs of infection. From that day on, Paré vowed never again to use the cruel hot oil to treat wounds.

In 1545, Paré popularized his wound treatments in his *Method of Treating Wounds*, thus leading the development of the humane “rational” practice of surgery. Another important contribution to medicine was his promotion of the ligature of blood vessels (e.g., tying off with twine) to prevent hemorrhage during amputations, instead of the traditional method of burning the stump with a hot iron. Paré also facilitated progress in obstetrics, using practices that ensured safer delivery of infants.

SEE ALSO Sutures (c. 3000 BCE) Antiseptics (1865), Heart Transplant (1967).

Artificial hand, from Ambroise Paré’s Instrumenta chyrurgiae et icones anathomicae (Surgical Instruments and Anatomical Illustrations), 1564, Paris.



1572

Imaginary Numbers • *Clifford A. Pickover*

Rafael Bombelli (1526–1572)

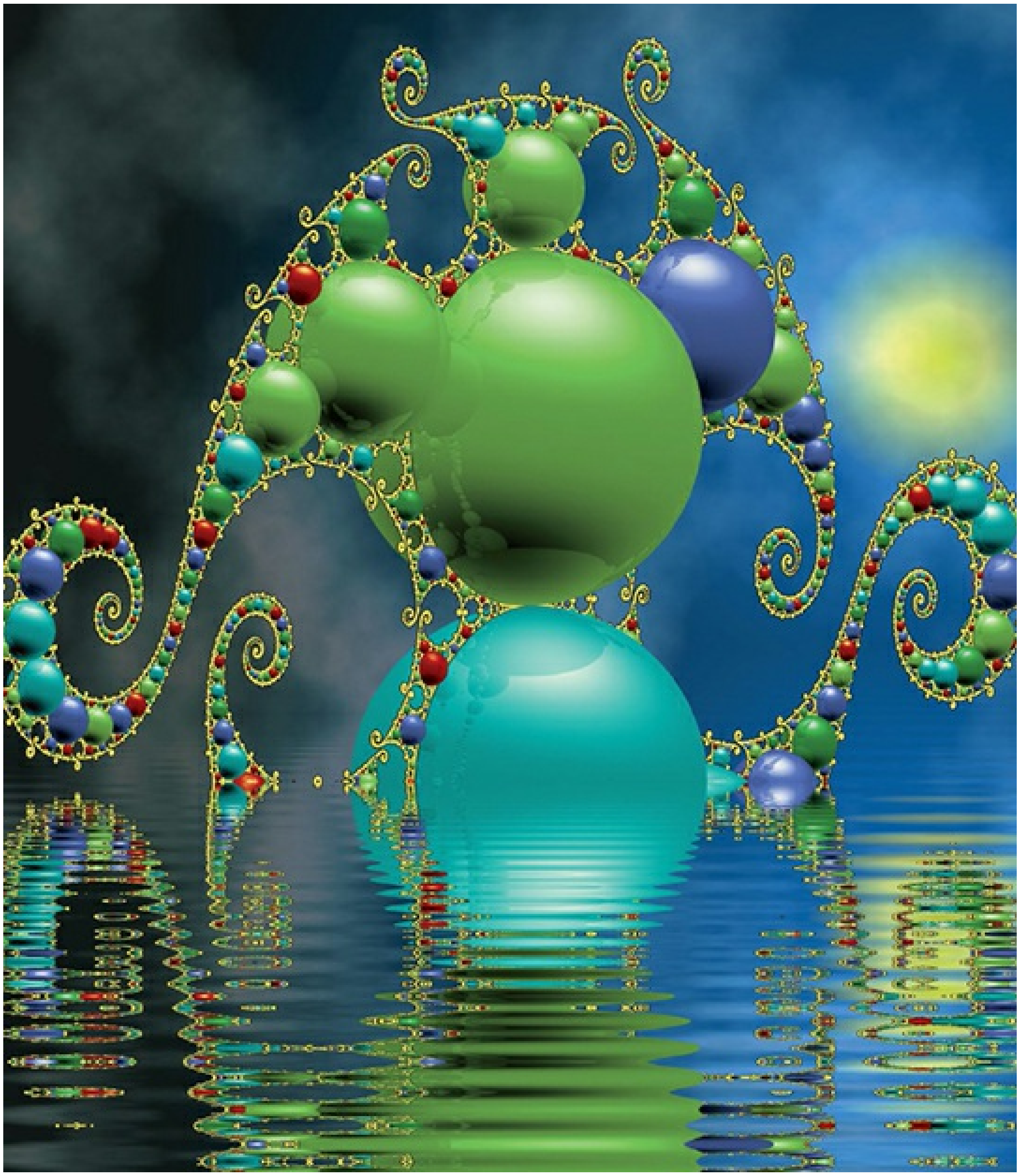
An imaginary number is one whose square has a negative value. The great mathematician Gottfried Leibniz called imaginary numbers “a wonderful flight of God’s Spirit; they are almost an amphibian between being and not being.” Because the square of any real number is positive, for centuries many mathematicians declared it impossible for a negative number to have a square root. Although various mathematicians had inklings of imaginary numbers, the history of imaginary numbers started to blossom in sixteenth-century Europe. The Italian engineer Rafael Bombelli, well known during his time for draining swamps, is today famous for his *Algebra*, published in 1572, that introduced a notation for $\sqrt{-1}$, which would be a valid solution to the equation $x^2 + 1 = 0$. He wrote, “It was a wild thought in the judgment of many.” Numerous mathematicians were hesitant to “believe” in imaginary numbers, including Descartes, who actually introduced the term *imaginary* as a kind of insult.

Leonhard Euler in the eighteenth century introduced the symbol i for $\sqrt{-1}$—for the first letter of the Latin word *imaginarius*—and we still use Euler’s symbol today. Key advances in modern physics would not have been possible without the use of imaginary numbers, which have aided physicists in a vast range of computations, including efficient calculations involving alternating currents, relativity theory, signal processing, fluid dynamics, and quantum mechanics. Imaginary numbers even play a role in the production of gorgeous fractal artworks that show a wealth of detail with increasing magnifications.

From string theory to quantum theory, the deeper one studies physics, the closer one moves to pure mathematics. Some might even say that mathematics “runs” reality in the same way that Microsoft’s operating system runs a computer. Schrödinger’s wave equation—which describes basic reality and events in terms of wave functions and probabilities—may be thought of as the evanescent substrate on which we all exist, and it relies on imaginary numbers.

SEE ALSO Euler’s Number, *e* (1727), Riemann Hypothesis (1859), Fractals (1975).

Imaginary numbers play a role in the production of Jos Leys’s gorgeous fractal artworks that show a wealth of detail with increasing magnifications. Early mathematicians were so suspicious of the usefulness of imaginary numbers that they insulted those who suggested their existence.



1608

Telescope • *Clifford A. Pickover*

Hans Lippershey (1570–1619), **Galileo Galilei** (1564–1642)

Physicist Brian Greene writes, “The invention of the telescope and its subsequent refinement and use by Galileo marked the birth of the modern scientific method and set the stage for a dramatic reassessment of our place in the cosmos. A technological device revealed conclusively that there is so much more to the universe than is available to our unaided senses.” Computer scientist Chris Langton agrees, noting, “Nothing rivals the telescope. No other device has initiated such a thoroughgoing reconstruction of our world view. It has forced us to accept the earth (and ourselves) as merely a part of the larger cosmos.”

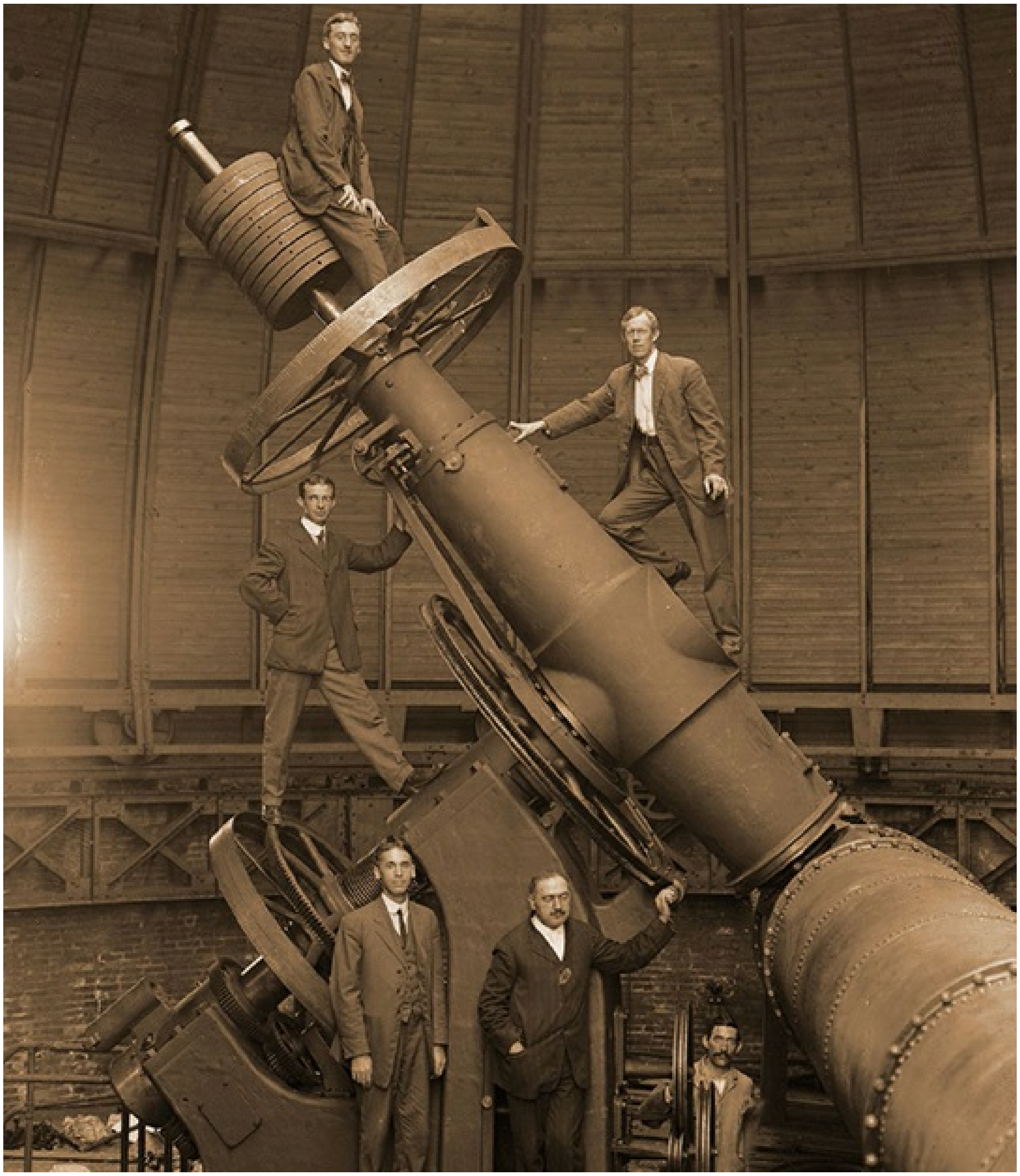
In 1608, the German-Dutch lensmaker Hans Lippershey may have been the first to invent the telescope, and a year later, the Italian astronomer Galileo

Galilei constructed a telescope with about a three-fold magnification. He later made others with up to a 30-fold magnification. Although the early telescopes were designed to observe remote objects using visible light, modern telescopes are a range of devices capable of utilizing other regions of the electromagnetic spectrum. *Refracting telescopes* employ lenses to form an image, while *reflecting telescopes* use an arrangement of mirrors for this purpose. *Catadioptric telescopes* use mirrors and lenses.

Interestingly, many important astronomical discoveries with telescopes have been largely unanticipated. Astrophysicist Kenneth Lang writes in *Science*, "Galileo Galilei turned his newly constructed spyglass to the skies, and thus began astronomers' use of novel telescopes to explore a universe that is invisible to the unaided eye. The search for the unseen has resulted in many important unexpected discoveries, including Jupiter's four large moons, the planet Uranus, the first asteroid Ceres, the large recession velocities of spiral nebulae, radio emission from the Milky Way, cosmic X-ray sources, Gamma-Ray Bursts, radio pulsars, the binary pulsar with its signature of gravitational radiation, and the Cosmic Microwave Background radiation. The observable universe is a modest part of a much vaster, undiscovered one that remains to be found, often in the least expected ways."

SEE ALSO Sun-Centered Universe (1534), Newton's Prism (1672), Hubble Telescope (1990).

LEFT: *One antenna in the Very Large Array (VLA) used for studying signals from radio galaxies, quasars, pulsars, and more.* RIGHT: *Observatory staff astride the University of Pittsburgh's Thaw 30-inch refractor just before its completion in 1913. A man sits atop counterweights needed to keep the massive telescope in balance.*



1609

Kepler’s Laws of Planetary Motion

Clifford A. Pickover

Johannes Kepler (1571–1630)

“Although Kepler is remembered today chiefly for his three laws of planetary motion,” writes astronomer Owen Gingerich, “these were but three elements in his much broader search for cosmic harmonies. . . . He left [astronomy] with a unified and physically motivated heliocentric [Sun-centered] system nearly 100 times more accurate.”

Johannes Kepler was the German astronomer and theologian-cosmologist, famous for his laws that described the elliptical orbits of the Earth and other planets around the Sun. In order for Kepler to formulate his laws, he had to first abandon the prevailing notion that circles were the “perfect” curves for describing the cosmos and its planetary orbits. When Kepler first expressed his laws, he had no theoretical justification for them. They simply provided an elegant means by which to describe orbital paths obtained from experimental data. Roughly 70 years later, Newton showed that Kepler’s Laws were a consequence of Newton’s *Law of Universal Gravitation*.

Kepler’s First Law (The Law of Orbits, 1609) indicated that all of the planets in our Solar System move in elliptical orbits, with the Sun at one focus. His Second Law (The Law of Equal Areas, 1618) showed that when a planet is far from the Sun, the planet moves more slowly than when it is close to the Sun. An imaginary line that connects a planet to the Sun sweeps out equal areas in equal intervals of time. Given Kepler’s first two laws, planetary orbits and positions could now be easily calculated and with an accuracy that matched observations.

Kepler's Third Law (The Law of Periods, 1618) showed that for any planet, the square of the period of its revolution about the Sun is proportional to the cube of the semi-major axis of its elliptical orbit. Thus, planets far from the Sun have very long years. Kepler's Laws are among the earliest scientific laws to be established by humans, and, while unifying astronomy and physics, the laws provided a stimulus to subsequent scientists who attempted to express the behavior of reality in terms of simple formulas.

SEE ALSO Antikythera Mechanism (c. 125 BCE), Sun-Centered Universe (1543), Telescope (1608), Newton's Laws of Motion and Gravitation (1687).

Artistic representation of the Solar System. Johannes Kepler was the German astronomer and theologian-cosmologist, famous for his laws that described the elliptical orbits of the Earth and the other planets around the sun.

1614

Logarithms • *Clifford A. Pickover*

John Napier (1550–1617)

Scottish mathematician John Napier is famous as the inventor and promoter of logarithms in his 1614 book *A Description of the Marvelous Rule of Logarithms*. This method has since contributed to countless advances in science and engineering by making difficult calculations possible. Before electronic calculators became widely available, logarithms and tables of logarithms were commonly used in surveying and navigation. Napier was also the inventor of Napier's bones, rods carved with multiplication tables that could be arranged in patterns in order to aid in calculations.

A logarithm (to a base b) of a number x is expressed as $\log_b(x)$ and equals the exponent y that satisfies $x = b^y$. For example, because $3^5 = 3 \times 3 \times 3 \times 3 \times 3 = 243$, we say that the log of 243 (base 3) is 5, or $\log_3(243) = 5$. As another example, $\log_{10}(100) = 2$. For practical purposes, consider that a multiplication such as $8 \times 16 = 128$ can be rewritten as $2^3 \times 2^4 = 2^7$, thereby converting the calculations into ones involving the simple additions of the powers ($3 + 4 = 7$). Prior to calculators, in order to multiply two numbers, an engineer often looked up the logarithms of both numbers in a table, added them, and then looked up the result in the table to find the product. This could often be faster than multiplying by hand and is the principle on which slide rules are based.

Today, various quantities and scales in science are expressed as logarithms of other quantities. For example, the pH scale in chemistry, the bel unit of measurement in acoustics, and the Richter scale used for measuring earthquake intensity all involve a base-10 logarithmic scale. Interestingly, the discovery of logarithms just prior to the era of Isaac Newton had an impact on science comparable to the invention of the computer in the twentieth century.

SEE ALSO Slide Rule (1621), Euler's Number, *e* (1727), ENIAC (1946).

John Napier, the discoverer of logarithms, created a calculation device known as Napier's rods or bones. Napier's rotatable rods reduced multiplication to a sequence of simple additions.


0 1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 6 7 8 9 10 11
2 3 4 5 6 7 8 9 10 11 12
3 4 5 6 7 8 9 10 11 12 13
4 5 6 7 8 9 10 11 12 13 14
5 6 7 8 9 10 11 12 13 14 15
6 7 8 9 10 11 12 13 14 15 16
7 8 9 10 11 12 13 14 15 16 17
8 9 10 11 12 13 14 15 16 17 18
9 10 11 12 13 14 15 16 17 18 19
10 11 12 13 14 15 16 17 18 19 20
11 12 13 14 15 16 17 18 19 20 21

1620

Scientific Method • *Michael C. Gerald with Gloria E. Gerald*

Aristotle (384–322 BCE), **Francis Bacon** (1561–1626), **Galileo Galilei** (1564–1642), **Claude Bernard** (1813–1878), **Louis Pasteur** (1822–1895)

Formulation and fine-tuning of the scientific method has evolved over the ages and is based upon the contributions of many early distinguished scholars including Aristotle, who introduced logical deduction, a “top-down” approach, that is, starting with a theory or hypothesis and then testing that theory; Francis Bacon, the father of the modern scientific method, who in 1620 wrote *Novum Organum Scientiarum*, which proposed inductive reasoning as the foundation for scientific reasoning, a “bottom-up” approach in which specific observations led to the formulation of a general theory or hypothesis; and Galileo, who advocated experimentation rather than metaphysical explanations. In the mid-nineteenth century, Louis Pasteur elegantly utilized the scientific method when he designed experiments to disprove the theory of spontaneous generation.

In 1865, Claude Bernard, one of the greatest of all scientists, wrote *An Introduction to the Study of Experimental Medicine*, which he personalized by using his own thoughts and experiments. In this classic book, he examined the importance of the scientist bringing forth new knowledge to society, and he then proceeded to critically analyze what constituted a good scientific theory, the importance of observation rather than reliance on historical authorities and sources, inductive and deductive reasoning, and cause and effect.

When some nonscientists think of theories, such as the theory of evolution, not infrequently they use the term “theory” disparagingly and assume or imply that it imputes an unproven notion or a mere guess or speculation. Scientists, by contrast, use the term “theory” to refer to an explanation, model, or general principle that has been tested and confirmed and that explains or predicts a natural event. The scientific method follows a number of sequential steps and is an approach used to investigate phenomena or acquire new knowledge. Using a series of steps, it is based upon developing and testing a hypothesis that explains a given observation, objectively evaluating the test results obtained, and then accepting, rejecting, or modifying that hypothesis. A theory is broader and more general than a hypothesis and is supported by experimental evidence based on a number of hypotheses that can be tested independently.

SEE ALSO Refuting Spontaneous Generation (1668), Darwin’s Theory of Natural Section (1859), Randomized Controlled Trials (1948), Placebo Effect (1955)

In Novum Organum (New Method), Bacon proposed a scientific method of inquiry based on inductive reasoning, in which a generalization is built based on incremental data collection. This method was intended to improve upon Aristotle’s deductive reasoning, which deduces specific facts from a generalization.

1621

Slide Rule • *Clifford A. Pickover*

William Oughtred (1574–1660)

Those of you who went to high school before the 1970s may recall that the slide rule once seemed to be as common as the typewriter. In just seconds, engineers could multiply, divide, find square roots, and do much more. The earliest version with sliding pieces was invented in 1621 by English mathematician and Anglican minister William Oughtred, based on the logarithms of Scottish mathematician John Napier. Oughtred may not have initially recognized the value of his work, because he did not quickly publish his findings. According to some accounts, one of his students stole the idea and published a pamphlet on the slide rule, which emphasized its portability, and raved that the device was "fit for use on horseback as on foot." Oughtred was outraged by his student's duplicity.

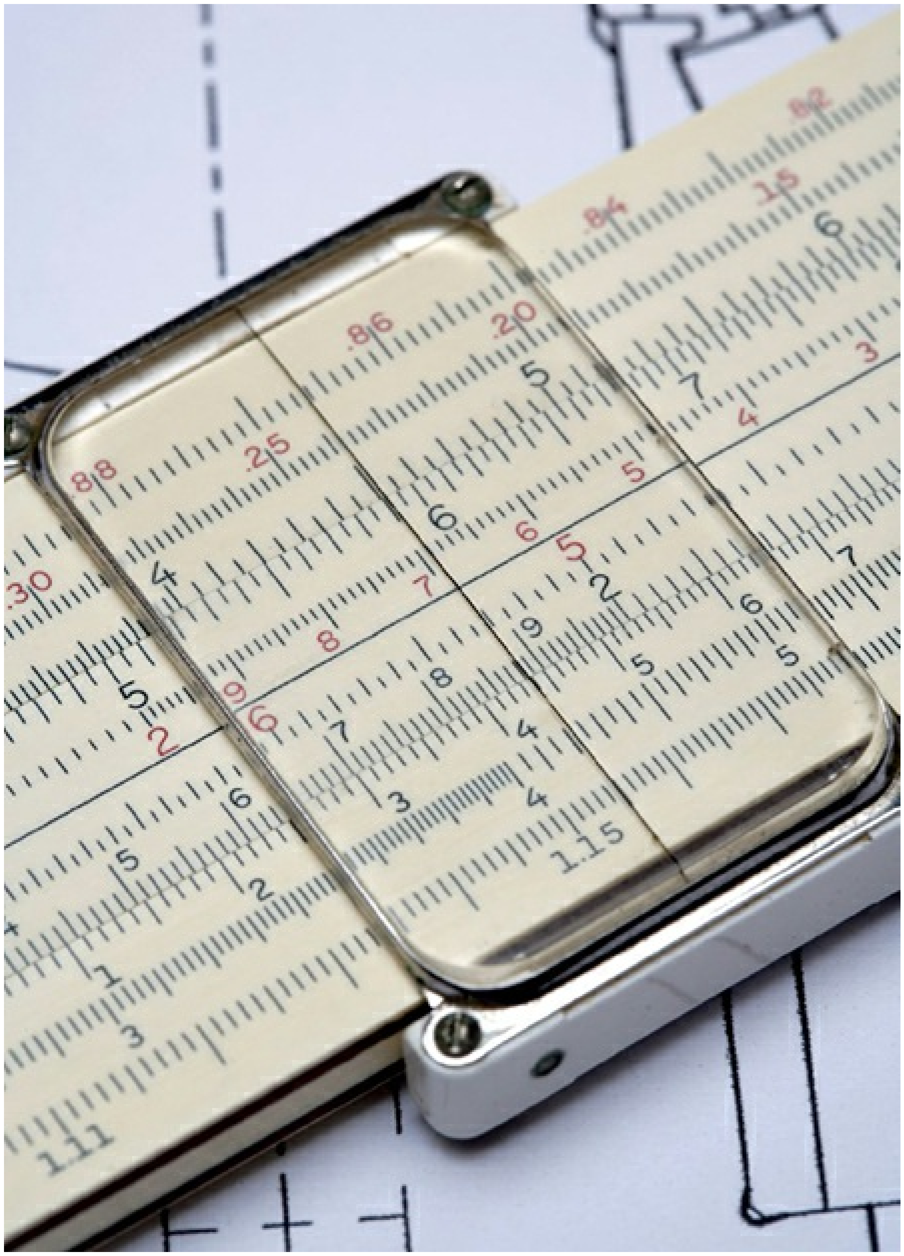
In 1850, a 19-year-old French artillery lieutenant modified the original design of the slide rule, and the French army used it to perform projectile calculations when fighting the Prussians. During World War II, American bombers often used specialized slide rules.

Slide-rule guru Cliff Stoll writes, "Consider the engineering achievements that owe their existence to rubbing two sticks together: the Empire State Building; the Hoover Dam; the curves of the Golden Gate Bridge; hydrodynamic automobile transmissions, transistor radios; the Boeing 707 airliner." Wernher Von Braun, the designer of the German V-2 rocket, relied on slide rules made by the German company Nestler, as did Albert Einstein. Pickett slide rules were aboard Apollo space missions in case the computers failed!

In the twentieth century, 40 million slide rules were produced worldwide.

Given the crucial role that this device played from the Industrial Revolution until modern times, the device deserves a place in this book. Literature from the Oughtred Society states, “For a span of 3.5 centuries, it was used to perform design calculations for virtually all the major structures built on this earth.”

SEE ALSO Ishango Bone (c. 18,000 BCE), Antikythera Mechanism (c. 125 BCE) Logarithms (1614), ENIAC (1946).

The slide rule played a crucial role from the Industrial Revolution until modern times. In the twentieth century, 40 million slide rules were produced and were used by engineers for countless applications.

1628

Circulatory System • *Clifford A. Pickover*

Praxagoras (340 BCE–280 BCE), **Ibn al-Nafis** (1213–1288), **Hieronymus Fabricius** (1537–1619), **William Harvey** (1578–1657), **Marcello Malpighi** (1628–1694)

Science journalist Robert Adler writes, “Today, the basics of how blood circulates through the body seem trivial. . . . Grade-school children learn that the heart pumps oxygen-rich blood through the body via the arteries, that the veins return oxygen-depleted blood to the heart, and that tiny capillaries link the finest arteries and veins. Yet . . . the functioning of the heart and blood vessels remained a profound mystery from ancient times until the first quarter of the seventeenth century.”

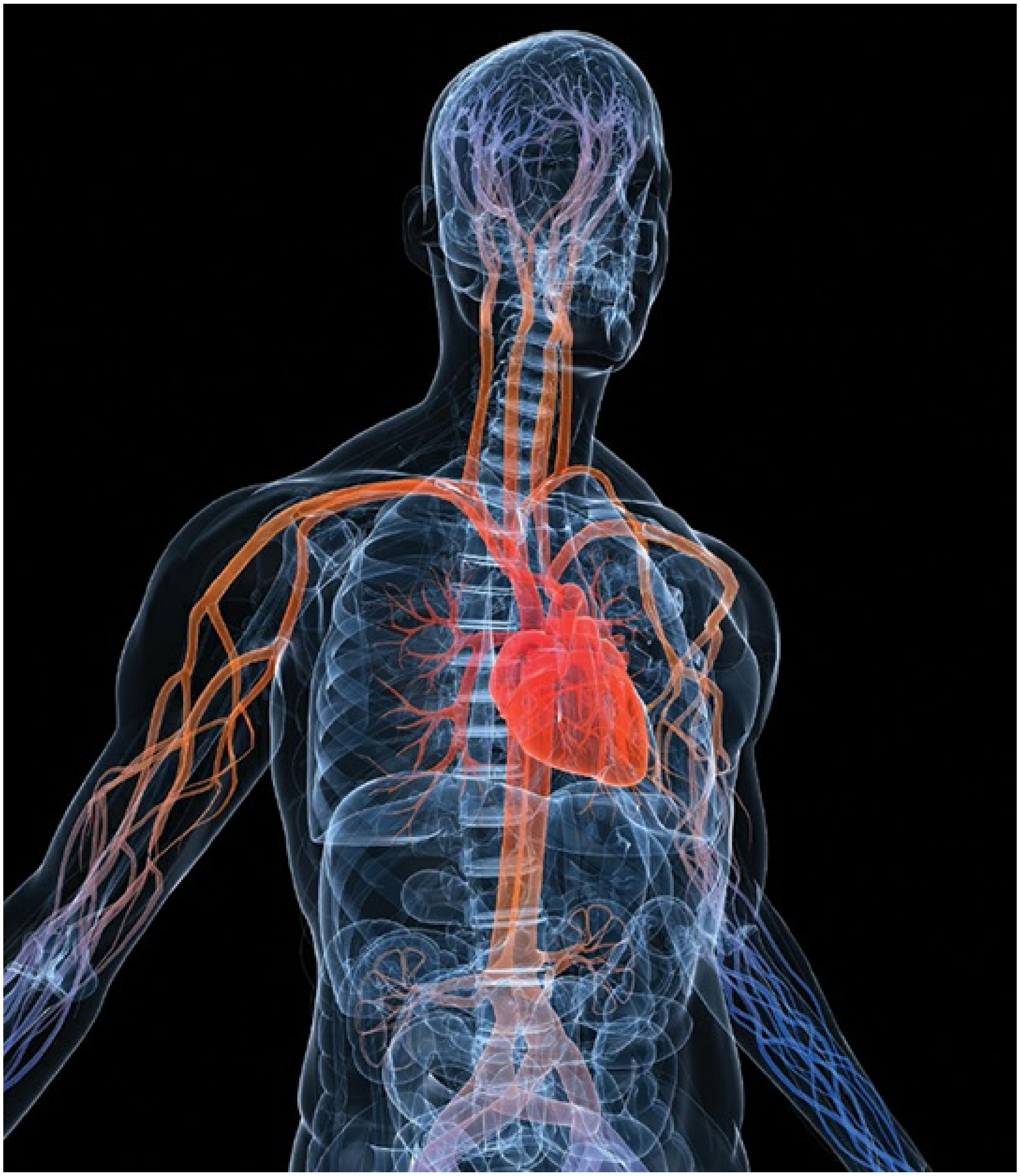
English physician William Harvey was the first to correctly describe, in detail, the circulation of blood through the body. In his 1628 work, *De motu cordis* (fuller title in English: *On the Motion of the Heart and Blood in Animals*), Harvey traced the correct route of blood through his study of living animals, in which he could pinch various blood vessels near the heart (or could cut vessels) and note directions of flow. He also applied pressure to veins near the skin of human subjects and noted blood-flow direction by observing swelling, along with the parts of the arms that grew congested or pale. In contrast to physicians of the past, who conjectured that the liver produced blood that was continually absorbed by the body, Harvey showed that blood must be recycled. He also realized that the valves that exist in veins, discovered by his teacher Hieronymus Fabricius, facilitated one-way blood flow to the heart.

Harvey traced the blood through smaller and smaller arteries and veins but did not have a microscope and, thus, could only conjecture that connections must exist between arteries and veins. Just a few years after Harvey died, Italian physician Marcello Malpighi used a microscope to observe the tiny capillaries that provided the elusive connections.

Various related work in blood circulation predates Harvey. For example, the Greek physician Praxagoras discussed arteries and veins, but he suggested that arteries carried air. In 1242, the Arab Muslim physician Ibn al-Nafis elucidated the flow of blood between the heart and lungs.

SEE ALSO Morgagni's "Cries of Suffering Organs" (1761), Blood Transfusion (1829), Heart Transplant (1967).

William Harvey correctly described, in detail, the circulation of blood through the body, including the path of oxygenated blood away from the heart and the return of deoxygenated blood back to the heart.



1637

Descartes’ *La Géométrie* • *Clifford A. Pickover*

René Descartes (1596–1650)

In 1637, French philosopher and mathematician René Descartes published *La géométrie*, which shows how geometrical shapes and figures can be analyzed using algebra. Descartes’ work influenced the evolution of analytical geometry, a field of mathematics that involves the representation of positions in a coordinate system and in which mathematicians algebraically analyze such positions. *La géométrie* also shows how to solve mathematical problems and discusses the representation of points of a plane through the use of real numbers, and the representation and classification of curves through the use of equations.

Interestingly, *La géométrie* does not actually use “Cartesian” coordinate axes or any other coordinate system. The book pays as much attention to representing algebra in geometric forms as vice versa. Descartes believed that algebraic steps in a proof should usually correspond to a geometrical representation.

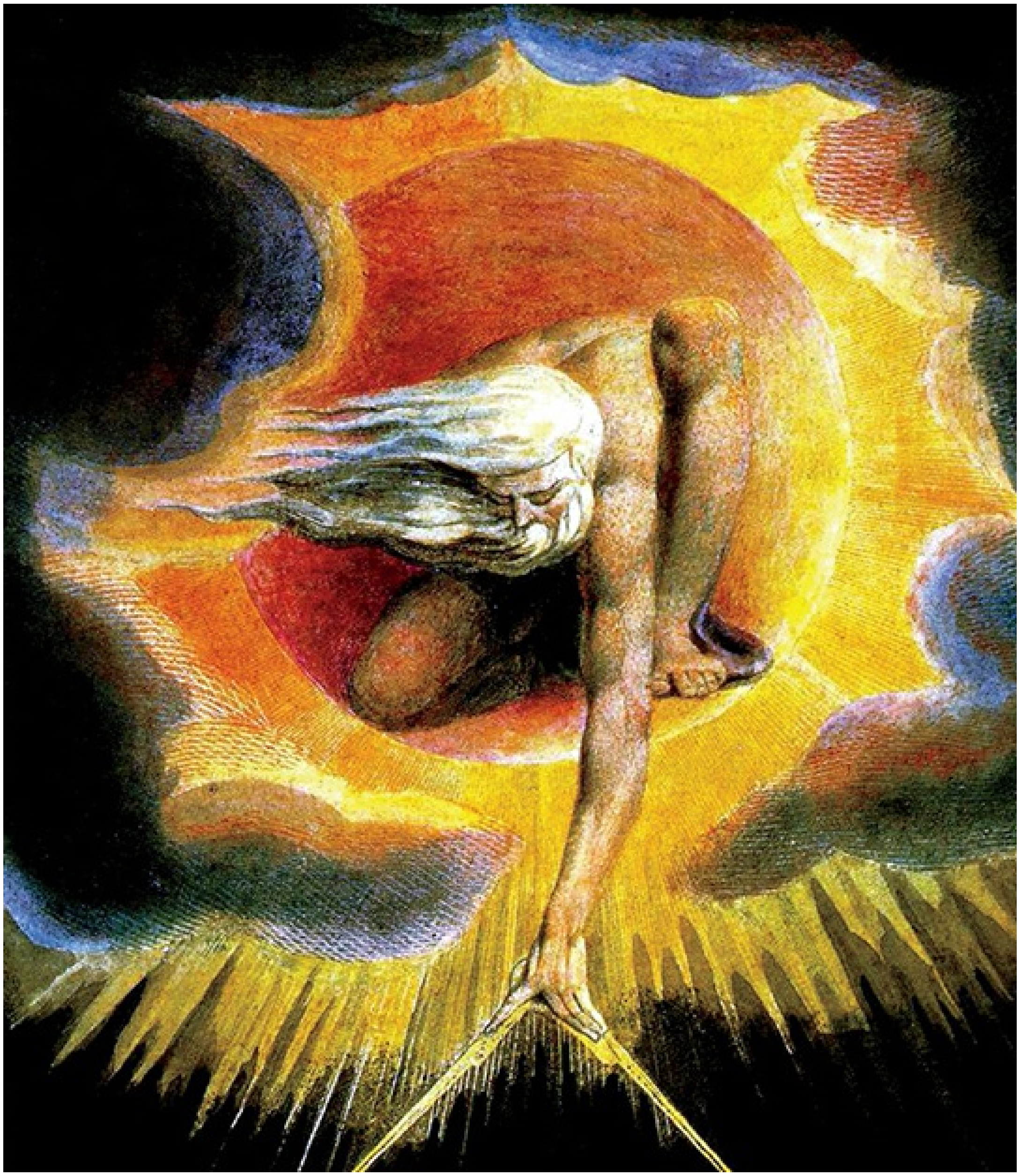
Jan Gullberg writes, “*La géométrie* is the earliest mathematical text that a modern student of mathematics could read without stumbling over an abundance of obsolete notations. . . . Along with Newton’s *Principia*, it is one of the most influential scientific texts of the seventeenth century.” According to Carl Boyer, Descartes desired to “free geometry” from the use of diagrams through algebraic procedures and to give meaning to the operations of algebra through geometric interpretation.

More generally, Descartes was groundbreaking in his proposal to unite algebra and geometry into a single subject. Judith Grabiner writes, “Just as the history of Western philosophy has been viewed as a series of footnotes to Plato, so the past 350 years of mathematics can be viewed as a series of footnotes to Descartes’ *Geometry* . . . and the triumph of Descartes’ methods of problem solving.”

Boyer concludes, “In terms of mathematical ability, Descartes probably was the most able thinker of his day, but he was at heart not really a mathematician.” His geometry was only one facet of a full life that revolved around science, philosophy, and religion.

SEE ALSO Pythagorean Theorem and Triangles (c. 600 BCE), Euclid’s *Elements* (c. 300 BCE).

The Ancient of Days (1794), a watercolor etching by William Blake. European medieval scholars often associated geometry and the laws of nature with the divine. Through the centuries, geometry’s focus on compass and straightedge constructions became more abstract and analytical.



1638

Acceleration of Falling Objects • *Clifford A. Pickover*

Galileo Galilei (1564–1642)

“To appreciate the full nature of Galileo’s discoveries,” writes I. Bernard Cohen, “we must understand the importance of abstract thinking, of its use by Galileo as a tool that in its ultimate polish was a much more revolutionary instrument for science than even the telescope.” According to legend, Galileo dropped two balls of different weights from the Leaning Tower of Pisa to demonstrate that they would both hit the ground at the same time. Although this precise experiment probably did not take place, Galileo certainly performed experiments that had a profound effect on contemporary understanding of the laws of motions. Aristotle had taught that heavy objects fall faster than light ones. Galileo showed that this was only an artifact of differing air resistances of the objects, and he supported his claims by performing numerous experiments with balls rolling down inclined planes. Extrapolating from these experiments, he demonstrated that if objects could fall without air resistance, all objects accelerate at the same rate. More precisely, he showed that the distance traveled by a constantly accelerating body starting at zero velocity is proportional to the square of the time falling.

Galileo also proposed the principle of inertia, in which an object’s motion continues at the same speed and direction unless acted upon by another force. Aristotle had erroneously believed that a body could be kept in motion only by applying a force. Newton later incorporated Galileo’s principle into his Laws of Motion. If it is not apparent to you that a moving object does not “naturally” stop moving without an applied force, you can imagine an experiment in which the face of a penny is sliding along an infinite smooth horizontal table that is so well oiled that there is no friction. Here, the penny would continue sliding along such an imaginary surface forever.

SEE ALSO Archimedes Principle of Buoyancy (c. 250 BCE) Newton's Laws of Motion and Gravitation (1687), Conservation of Energy (1843).

Imagine spheres, or any objects, of different masses released at the same height at the same time. Galileo showed that they must all fall together at the same speed, if we neglect any differences in air resistance.

1639

Projective Geometry • *Clifford A. Pickover*

Leon Battista Alberti (1404–1472), **Gérard Desargues** (1591–1661), **Jean-Victor Poncelet** (1788–1867)

Projective geometry generally concerns the relationships between shapes and their mappings, or "images," that result from projecting the shapes onto a surface. Projections may often be visualized as the shadows cast by objects.

The Italian architect Leon Battista Alberti was one of the first individuals to experiment with projective geometry through his interest in perspective in art. More generally, Renaissance artists and architects were concerned with methods for representing three-dimensional objects in two-dimensional drawings. Alberti sometimes placed a glass screen between himself and the landscape, closed one eye, and marked on the glass certain points that appeared to be in the image. The resulting 2-D drawing gave a faithful impression of the 3-D scene.

French mathematician Gérard Desargues was the first professional mathematician to formalize projective geometry while searching for ways to extend Euclidean geometry. In 1636, Desargues published *Exemple de l'une des manières universelles du S.G.D.L. touchant la pratique de la perspective* (*Example of a Universal Method by Sieur Girard Desargues Lyonnais Concerning the Practice of Perspective*), in which he presented a geometric method for constructing perspective images of objects. Desargues also examined the properties of shapes that were preserved under perspective mappings. Painters and engravers made use of his approach.

Desargues' most important work, *Brouillon project d'une atteinte aux événements des rencontres d'un cône avec un plan* (*Rough Draft of Attaining *the Outcome of Intersecting a Cone with a Plane*), published in 1639, treats the theory of conic sections using projective geometry. In 1882, French mathematician and engineer Jean-Victor Poncelet (1788–1867) published a treatise that revitalized interest in projective geometry.

In projective geometry, elements such as points, lines, and planes generally remain points, lines, and planes when projected. However, lengths, ratios of lengths, and angles may change under projection. In projective geometry, parallel lines in Euclidean geometry intersect at infinity in the projection.

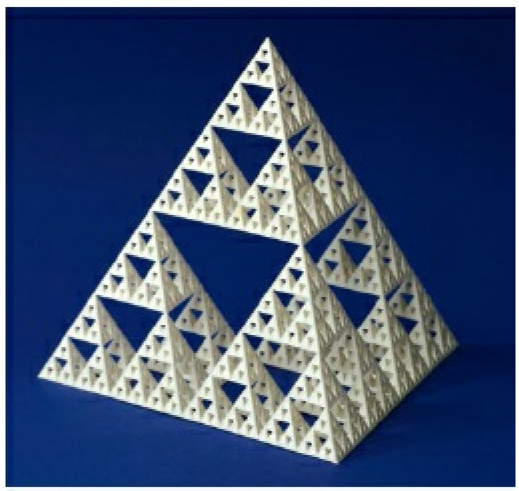
SEE ALSO Euclid's *Elements* (c. 300 BCE), Descartes' *La Géométrie* (1637), Tesseract (1888).

Drawing by Jan Vredeman de Vries (1527–c. 1607), a Dutch Renaissance architect and engineer who experimented with the principles of perspective in his artwork. Projective geometry grew from the principles of perspective art established during the European Renaissance.

1654

Pascal’s Triangle • *Clifford A. Pickover*

Blaise Pascal (1623–1662), **Omar Khayyam** (1048–1131)



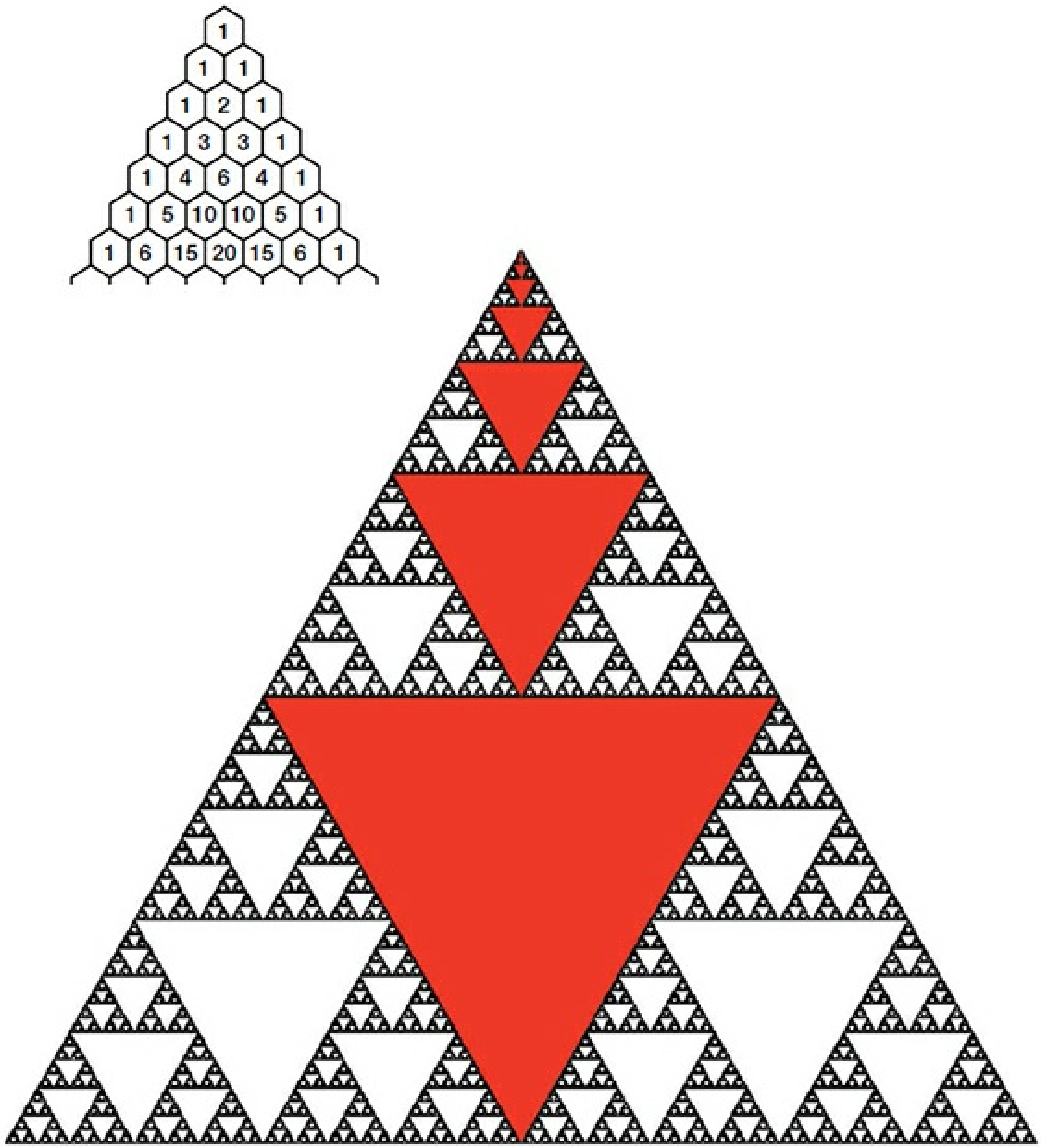
One of the most famous integer patterns in the history of mathematics is Pascal’s triangle. Blaise Pascal was the first to write a treatise about this progression in 1654, although the pattern had been known by the Persian poet and mathematician Omar Khayyam as far back as A.D. 1100, and even earlier to the mathematicians of India and ancient China. The first seven rows of Pascal’s triangle are depicted at upper right.

Each number in the triangle is the sum of the two above it. Mathematicians have discussed the role that Pascal’s triangle plays in probability theory, in the expansion of binomials of the form $(x + y)^n$, and in various number theory applications for years. Mathematician Donald Knuth (b. 1938) once indicated that there are so many relations and patterns in Pascal’s triangle that when someone finds a new identity, there aren’t many people who get excited about it anymore, except the discoverer. Nonetheless, fascinating studies have revealed countless wonders, including special geometric patterns in the diagonals, the existence of perfect square patterns with various hexagonal properties, and an extension of the triangle and its patterns to negative integers and to higher dimensions.

When even numbers in the triangle are replaced by dots and odd numbers by gaps, the resulting pattern is a fractal, with intricate repeating patterns on different size scales. These fractal figures may have a practical importance in that they can provide models for materials scientists to help produce new structures with novel properties. For example, in 1986, researchers created wire gaskets on the micron size scale almost identical to Pascal's triangle, with holes for the odd numbers. The area of their smallest triangle was about 1.38 microns squared, and the scientists investigated many unusual properties of their superconducting gasket in a magnetic field.

SEE ALSO Normal Distribution Curve (1733), Cellular Automata (1952), Fractals (1975).

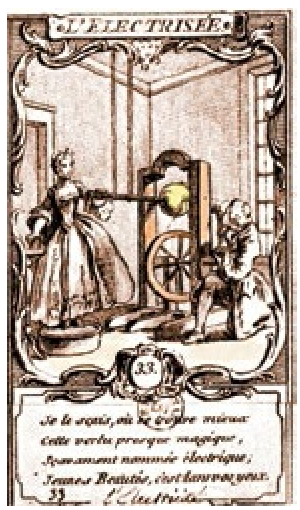
LEFT: *George W. Hart created this nylon model of Pascal's pyramid using a physical process known as selective laser sintering.* RIGHT: *The fractal Pascal triangle discussed in the text. The number of cells in the central red triangles is always even (6, 28, 120, 496, 2,016. . . .) and includes all perfect numbers (numbers that are the sum of their proper positive divisors).*


1
1 1
1 2 1
1 3 3 1
1 4 6 4 1
1 5 10 10 5 1
1 6 15 20 15 6 1

1660

Von Guericke’s Electrostatic Generator • *Clifford A. Pickover*

Otto von Guericke (1602–1686), **Robert Jemison Van de Graaff** (1901–1967)



Neurophysiologist Arnold Trehub writes, “The most important invention in the past two thousand years must be a seminal invention with the broadest and most significant consequences. In my opinion, it is the invention by Otto von Guericke of a machine that produced static electricity.” Although electrical phenomena were known by 1660, von Guericke appears to have produced the forerunner of the first machine for generating electricity. His electrostatic generator employed a globe made of sulfur that could be rotated and rubbed by hand. (Historians are not clear if his device was continuously rotated, a feature that would make it more easy to label his generator a machine.)

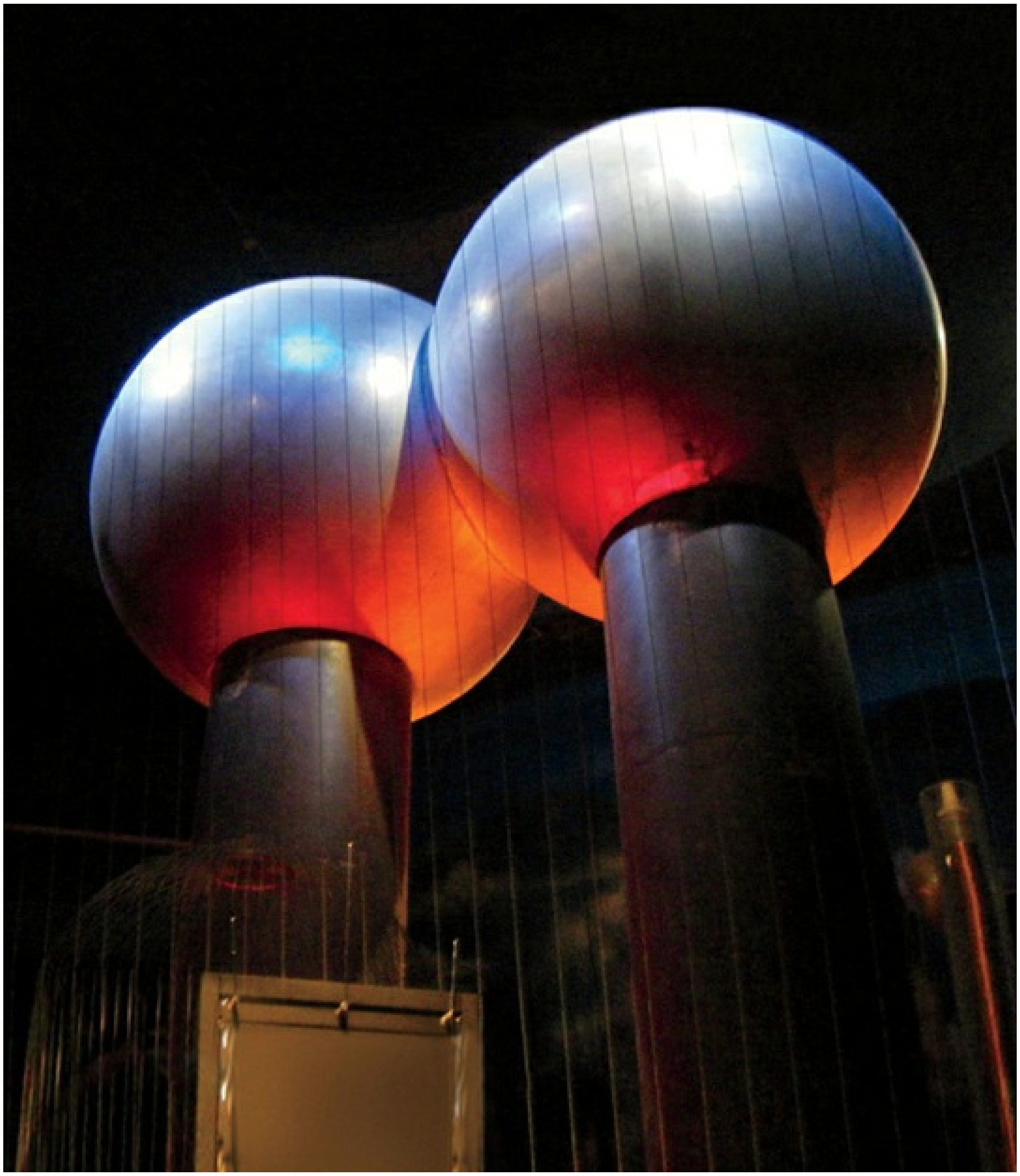
More generally, an electrostatic generator produces static electricity by transforming mechanical work into electric energy. Toward the end of the 1800s, electrostatic generators played a key role in research into the structure of matter. In 1929, an electrostatic generator known as the *Van de Graaff generator* (VG) was designed and built by American physicist Robert Van de Graaff, and it has been used extensively in nuclear physics research. Author William Gurstelle writes, “The biggest, brightest, angriest, and most fulgent electrical discharges don’t come from Wimshurst-style electrostatic machines [see Leyden Jar] . . . or Tesla coils either. They come from an auditorium-sized pair of tall cylindrical machines . . . called Van De Graaff generators, [which] produce cascades of sparks, electrical effluvia, and strong electric fields. . . .”

VGs employ an electronic power supply to charge a moving belt in order to accumulate high voltages, usually on a hollow metal sphere. To use VGs in a particle accelerator, a source of ions (charged particles) is accelerated by the voltage difference. The fact that the VG produces precisely controllable voltages allowed VGs to be used in studies of nuclear reactions during the designing of the atomic bomb.

Over the years, electrostatic accelerators have been used for cancer therapies, for semiconductor production (via ion implantation), for electron-microscope beams, for sterilizing food, and for accelerating protons in nuclear physics experiments.

SEE ALSO Coulomb’s Law of Electrostatics (1785), Battery (1800), Electron (1897), Little Boy Atomic Bomb (1945).

LEFT: *Von Guericke invented perhaps the first electrostatic generator, a version of which is illustrated in Hubert-François Gravelot’s engraving (c. 1750).* RIGHT: *World’s largest air-insulated Van de Graaff generator, originally designed by Van de Graaff for early atomic energy experiments and currently operating in the Boston Museum of Science.*



c. 1665

Development of Modern Calculus •

Clifford A. Pickover

Isaac Newton (1642–1727), **Gottfried Wilhelm Leibniz** (1646–1716)

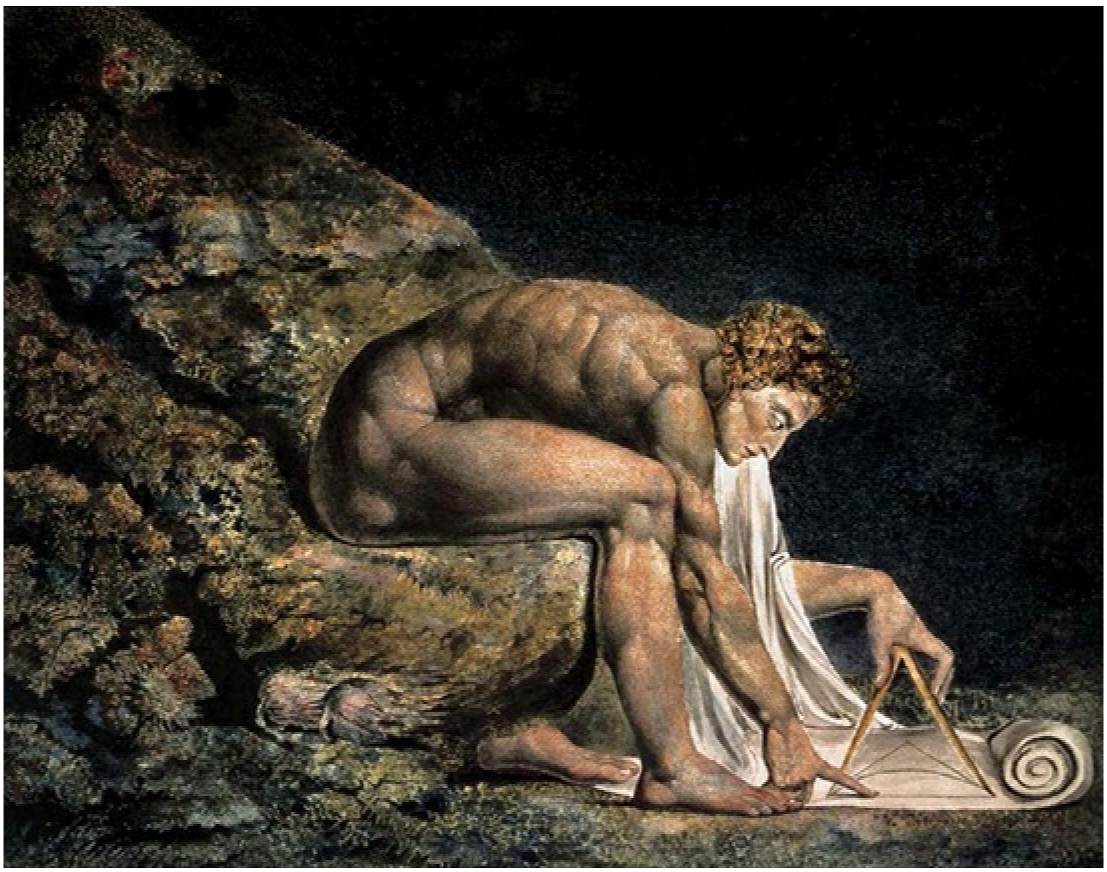
English mathematician Isaac Newton and German mathematician Gottfried Wilhelm Leibniz are usually credited with the invention of calculus, but various earlier mathematicians explored the concept of rates and limits, starting with the ancient Egyptians who developed rules for calculating the volume of pyramids and approximating the areas of circles.

In the 1600s, both Newton and Leibniz puzzled over problems of tangents, rates of change, minima, maxima, and infinitesimals (unimaginably tiny quantities that are almost but not quite zero). Both men understood that differentiation (finding the tangent to a curve at a point—that is, a straight line that "just touches" the curve at that point) and integration (finding the area under a curve) are inverse processes. Newton's discovery (1665–1666) started with his interest in infinite sums; however, he was slow to publish his findings. Leibniz published his discovery of differential calculus in 1684 and of integral calculus in 1686. He said, "It is unworthy of excellent men, to lose hours like slaves in the labor of calculation. . . . My new calculus . . . offers truth by a kind of analysis and without any effort of imagination." Newton was outraged. Debates raged for many years on how to divide the credit for the discovery of calculus, and, as a result, progress in calculus was delayed. Newton was the first to apply calculus to problems in physics, and Leibniz developed much of the notation seen in modern calculus books.

Today, calculus has invaded every field of scientific endeavor and plays invaluable roles in biology, physics, chemistry, economics, sociology, and engineering, and in any field where some quantity, like speed or temperature, changes. Calculus can be used to help explain the structure of a rainbow, teach us how to make more money in the stock market, guide a spacecraft, make weather forecasts, predict population growth, design buildings, and analyze the spread of diseases. Calculus has caused a revolution. It has changed the way we look at the world.

SEE ALSO Early Calculus (c. 1500), Newton's Laws of Motion and Gravitation (1687), Fourier Series (1807), Laplace's *Théorie Analytique des Probabilités* (1812).

William Blake's Newton (1795). Blake, a poet and artist, portrays Isaac Newton as a kind of divine geometer, gazing at technical diagrams drawn on the ground as he ponders mathematics and the cosmos.



1665

Micrographia • *Clifford A. Pickover*

Marcello Malpighi (1628–1694), **Anton Philips van Leeuwenhoek** (1632–1723), **Robert Hooke** (1635–1703), **Georgios Nicholas Papanikolaou** (1883–1962)

Although microscopes had been available since about the late 1500s, the use of the compound microscope (a microscope with more than one lens) by English scientist Robert Hooke represents a particularly notable milestone, and his instrument can be considered an important optical and mechanical forerunner of the modern microscope. For an optical microscope with two lenses, the overall magnification is the product of the powers of the ocular (eyepiece lens) and the objective lens, which is positioned closer to the specimen.

Hooke's 1665 book *Micrographia* featured breathtaking microscopic observations and biological speculation on specimens that ranged from plants to fleas. The book also discussed planets, the wave theory of light, and the origin of fossils, while stimulating both public and scientific interest in the power of the microscope.

Hooke was first to discover biological cells and coined the word *cell* to describe the basic units of all living things. The word *cell* was motivated by his observations of plant cells that reminded him of cellulae, which were the quarters in which monks lived. About this magnificent work, the historian of science Richard Westfall writes, "Robert Hooke's *Micrographia* remains one of the masterpieces of seventeenth century science, [presenting] a bouquet of observations with courses from the mineral, animal and vegetable kingdoms."

In 1673, Dutch biologist Anton van Leeuwenhoek discovered living organisms in a drop of pond water, opening up the possibility of using the microscope in medical research. He later published pictures of red blood cells, bacteria, spermatozoa, muscle tissue, and capillaries, the last of which were also observed by Italian physician Marcello Malpighi. Through the years, the microscope has become essential in research into the causes of diseases, such as bubonic plague, malaria, and sleeping sickness. The device also plays a crucial role in the study of cells, such as when used in the Pap smear test (invented by Greek physician Georgios Papanikolaou) to detect premalignant and malignant (cancerous) cervical cells. Before this test became widely used around 1943, cervical cancer was the leading cause of death in American women.

SEE ALSO Eyeglasses (1284), Discovery of Sperm (1678), Zoo Within Us (1683), Cell Division (1855), Germ Theory of Disease (1862).

Flea, from Robert Hooke's Micrographia (1665).

1668

Refuting Spontaneous Generation

Michael C. Gerald with Gloria E. Gerald

Aristotle (384–322 BCE), **Francesco Redi** (1626–1697), **Lazzaro Spallanzani** (1729–1799), **Louis Pasteur** (1822–1895)

In his book, *The History of Animals*, written over 2,000 years ago, Aristotle proclaimed that while some organisms arise from similar organisms, others, such as insects, arise spontaneously from putrefying earth or vegetable matter. Each spring, the ancients observed that the Nile overflowed its banks leaving behind muddy soil and frogs that were not present in dry times. In Shakespeare's *Antony and Cleopatra*, we learn that crocodiles and snakes are formed in the mud of the Nile. The concept that some living beings could arise from nonliving inanimate matter, which Aristotle called s*pontaneous generation*, remained essentially unchallenged until the seventeenth century. After all, it was commonly observed that maggots appeared to arise from decaying flesh.

In 1668, the Italian physician and poet Francesco Redi devised an experiment that questioned the validity of spontaneous generation and the origin of maggots from rotting meat. Redi placed meat in three widemouthed jars, which he set aside for several days. In the one that was open, flies reached the meat and laid their eggs. In another jar that was sealed, no flies or maggots were found. The mouth of the third was covered with gauze, preventing flies from entering the jar containing meat but upon which they laid their eggs that hatched into maggots.

One century later, Lazzaro Spallanzani, an Italian priest and biologist, boiled broth in a sealed container and permitted the air to escape. While he did not see the growth of any living organism, the question persisted as to whether air was an essential factor required for spontaneous generation to occur.

In 1859 the French Academy of Sciences sponsored a contest for the best experiment that would conclusively prove or disprove the validity of spontaneous generation. In his winning entry, Louis Pasteur placed boiled meat broth in a swan-necked flask, with the neck curved downward. This allowed the free flow of air into the flask, while preventing the entrance of airborne microbes. The broth-containing flask remained free of growth, and the concept of spontaneous generation was believed to be relegated to history.

SEE ALSO Darwin's Theory of Natural Section (1859), Germ Theory of Disease (1862), Miller-Urey Experiment (1952).

Louis Pasteur, a French microbiologist and chemist, made significant discoveries relating to the germ causes of disease, vaccinations, fermentation, and pasteurization.

1672

Measuring the Solar System • *Clifford A. Pickover*

Giovanni Domenico Cassini (1625–1712)

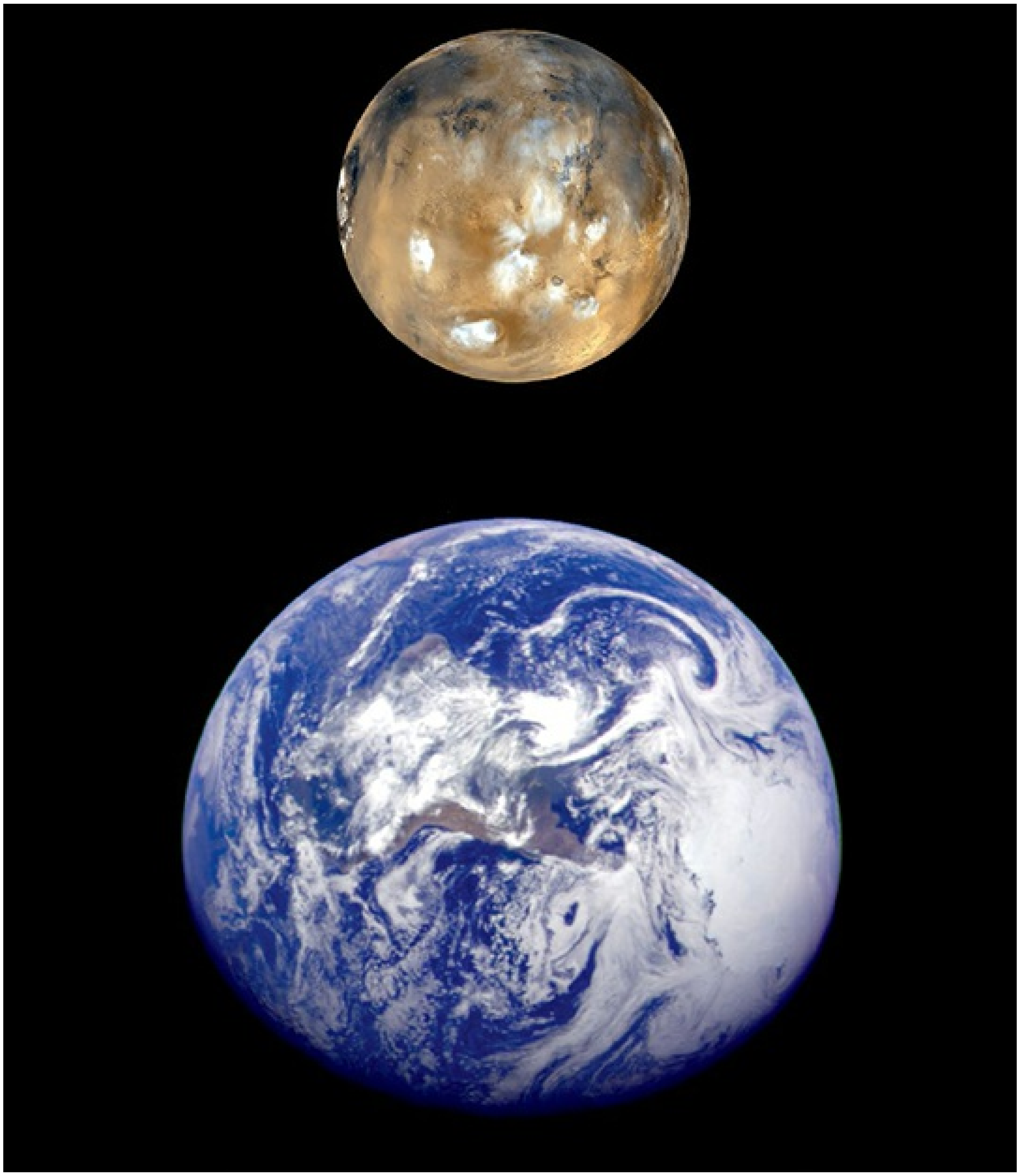
Before astronomer Giovanni Cassini's 1672 experiment to determine the size of the Solar System, there were some rather outlandish theories floating about. Aristarchus of Samos in 280 BCE had said that the Sun was a mere 20 times farther from the Earth than the Moon. Some scientists around Cassini's time suggested that stars were only a few million miles away. While in Paris, Cassini sent astronomer Jean Richer to the city of Cayenne on the northeast coast of South America. Cassini and Richer made simultaneous measurements of the angular position of Mars against the distant stars. Using simple geometrical methods, and knowing the distance between Paris and Cayenne, Cassini determined the distance between the Earth and Mars. Once this distance was obtained, he employed Kepler's Third Law to compute the distance between Mars and the Sun (see "Kepler's Laws of Planetary Motion"). Using both pieces of information, Cassini determined that the distance between the Earth and the Sun was about 87 million miles (140 million kilometers), which is only seven percent less than the actual average distance. Author Kendall Haven writes, "Cassini's discoveries of distance meant that the universe was millions of times bigger than anyone had dreamed." Note that it would be difficult to make direct measurements of the Sun without risking his eyesight.

Cassini became famous for many other discoveries. For example, he discovered four moons of Saturn and discovered the major gap in the rings of Saturn, which, today, is called the Cassini Gap in his honor. Interestingly, he was among the earliest scientists to correctly suspect that light traveled at a finite speed, but he did not publish his evidence for this theory because, according to Kendall Haven, “He was a deeply religious man and believed that light was of God. Light therefore had to be perfect and infinite, and not limited by a finite speed of travel.”

Since the time of Cassini, our concept of the Solar System has grown, with the discovery, for example, of Uranus (1781), Neptune (1846), Pluto (1930), and Eris (2005).

SEE ALSO Eratosthenes Measures Earth (c. 240 BCE) Sun-Centered Universe (1534), Kepler’s Laws of Planetary Motion (1609), Michelson-Morley Experiment (1887).

Cassini calculated the distance from Earth to Mars, and then the distance from Earth to the Sun. Shown here is a size comparison between Mars and Earth; Mars has approximately half the radius of Earth.



1672

Newton’s Prism • *Clifford A. Pickover*

Isaac Newton (1642–1727)

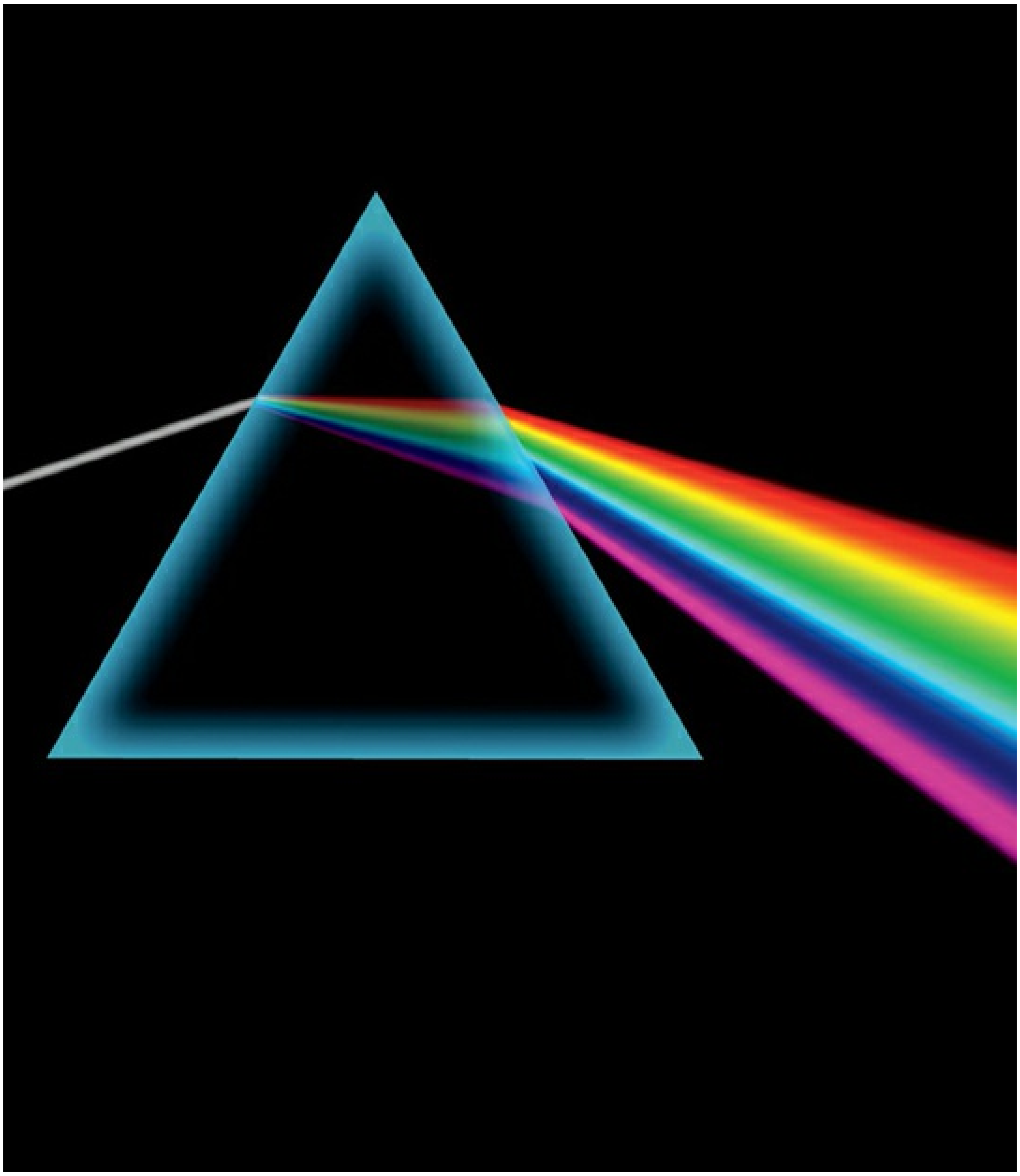
“Our modern understanding of light and color begins with Isaac Newton,” writes educator Michael Douma, “and a series of experiments that he publishes in 1672. Newton is the first to understand the rainbow—he refracts white light with a prism, resolving it into its component colors: red, orange, yellow, green, blue and violet.”

When Newton was experimenting with lights and colors in the late 1660s, many contemporaries thought that colors were a mixture of light and darkness, and that prisms colored light. Despite the prevailing view, he became convinced that white light was not the single entity that Aristotle believed it to be but rather a mixture of many different rays corresponding to different colors. The English physicist Robert Hooke criticized Newton’s work on the characteristics of light, which filled Newton with a rage that seemed out of proportion to the comments Hooke had made. As a result, Newton withheld publication of his monumental book *Opticks* until after Hooke’s death in 1703—so that Newton could have the last word on the subject of light and could avoid all arguments with Hooke. In 1704, Newton’s *Opticks* was finally published. In this work, Newton further discusses his investigations of colors and the diffraction of light.

Newton used triangular glass prisms in his experiments. Light enters one side of the prism and is refracted by the glass into various colors (since their degree of separation changes as a function of the wavelength of the color). Prisms work because light changes speed when it moves from air into the glass of the prism. Once the colors were separated, Newton used a second prism to refract them back together to form white light again. This experiment demonstrated that the prism was not simply adding colors to the light, as many believed. Newton also passed only the red color from one prism through a second prism and found the redness unchanged. This was further evidence that the prism did not create colors, but merely separated colors present in the original light beam.

SEE ALSO Wave Nature of Light (1801), Electromagnetic Spectrum (1864), Incandescent Light Bulb (1878).

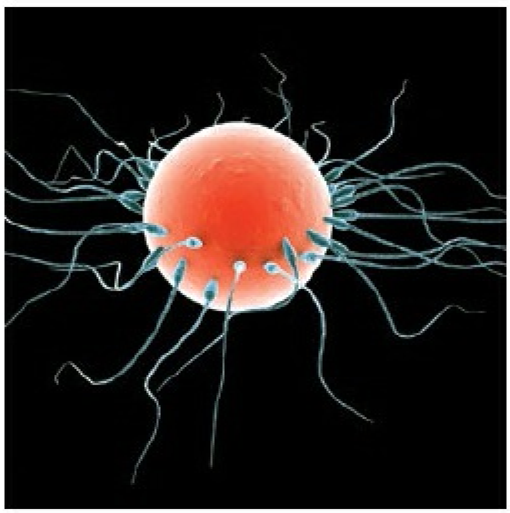
Newton used prisms to show that white light was not the single entity that Aristotle believed it to be, but rather was a mixture of many different rays corresponding to different colors.



1678

Discovery of Sperm • *Clifford A. Pickover*

Anton Philips van Leeuwenhoek (1632–1723), **Nicolaas Hartsoeker** (1656–1725)



In 1678, Dutch scientist Anton van Leeuwenhoek reported to the Royal Society on the discovery of human spermatozoa, which resembled innumerable wormlike animals. He wrote, “What I investigate is only what, without sinfully defiling myself, remains as a residue after conjugal coitus. And if your Lordship should consider that these observations may disgust or scandalize the learned, I earnestly beg your Lordship to regard them as private and to publish or destroy them as your Lordship thinks fit.” Van Leeuwenhoek eventually suggested that the minute microscopic creatures swimming in semen played a role in fertilization. Other scientists believed that the sperm were simply parasites and had nothing to do with the reproductive process.

Around 1677, van Leeuwenhoek and his student Johan Ham had used a microscope that magnified 300 times to examine spermatozoa, which he described as animalcules (little animals)—suggestive of his belief in preformation, a version of which posited that the head of each sperm cell contained a tiny, fully formed human. Dutch microscopist Nicolaas Hartsoeker claimed to have seen spermatozoa in 1674, but he was uncertain about his observations and, at first, thought the wriggling cells were parasites. His famous drawing of a homunculus, or little human, crammed within the head of a sperm suggested preformation as well. Hartsoeker did not claim to have seen actual homunculi, but other researchers did! Some suggested that the homunculi in sperm might have smaller sperm of their own, in an infinite regress of homunculi within homunculi. Of course, when researchers began to show how organs in creatures such as chicks gradually appear in the process of development, it became clear that animals are not in a near-final form from the start.

The word *sperm* generally refers to the male reproductive cell, and *spermatozoan* refers specifically to a mobile sperm cell with an attached, whiplike tail. Today we know that in humans, the sperm cell has 23 chromosomes (threadlike carriers of genetic information) that join with the 23 chromosomes in the female egg when fertilization occurs.

SEE ALSO *Micrographia* (1665), Chromosomal Theory of Inheritance (1902), Birth-Control Pill (1955).

LEFT: *Sperm surrounding an egg just prior to fertilization.* RIGHT: *Illustration of a sperm, emphasizing the head, whiplike tail, and joining midpiece, which contains a filamentous core with many energy-producing mitochondria for tail movement and propulsion.*

1683

Zoo Within Us • *Clifford A. Pickover*

Anton Philips van Leeuwenhoek (1632–1723)

Even healthy bodies contain a vast zoo of microbes affecting our health. The proper balance and functioning of this diverse ecosystem of bacteria, fungi, and viruses may hold cures to maladies ranging from inflammatory bowel diseases to various skin disorders. Interestingly, our bodies contain at least ten times as many of these tiny microbes (mostly in our intestines) than human cells, making our individual bodies behave like "superorganisms" of interacting species that, together, affect our well-being. One of the earliest discoveries of this microbiome zoo occurred in 1683, when Dutch microbiologist Anton van Leeuwenhoek used his home-built microscope to study scrapings of his own dental plaque and, to his surprise, found "little living animalcules, very prettily a-moving" in the specimen.

Beneficial and harmful microbes typically reside on and in the skin, mouth, gastrointestinal tract, vagina, nose, and other various orifices. More than 500 species of bacteria live in the human intestines, motivating researchers to think of this population as comprising a "virtual organ." The creatures in our gut can ferment food to aid in digestion, produce vitamins for our bodies, and prevent the growth of harmful species. Such bacteria rapidly colonize a baby's intestines starting from birth. Researchers are studying the possible role of different bacterial populations in diseases of the intestine (e.g., ulcerative colitis), tumor formation, and obesity. Researchers have also shown the importance of microbial diversity in the progression of cystic fibrosis (a genetic disease that can cause lung scarring) and continue to study possible roles of the microbial zoo in affecting the severity of eczema, psoriasis, Parkinson's, diabetes, and a variety of autoimmune diseases.

Using helminthic therapy, physicians and their patients experiment with the deliberate infestation of the intestines with helminths (parasitic worms such as hookworms and whipworms), which, in some cases, may have a beneficial role in ameliorating inflammatory bowel diseases, multiple sclerosis, asthma, and certain skin diseases by helping to modulate the functioning of the body's immune system.

SEE ALSO Sewage Systems (c. 600 BCE), *Micrographia* (1655), Discovery of Sperm (1678), Germ Theory of Disease (1862), Antiseptics (1865).

Electron micrograph of a cluster of salami-shaped E. coli bacteria. E. coli normally colonize an infant's gastrointestinal tract within a day or two after birth.

1687

Newton as Inspiration • *Clifford A. Pickover*

Isaac Newton (1642–1727)

The chemist William H. Cropper writes, “Newton was the greatest creative genius that physics has ever seen. None of the other candidates for the superlative (Einstein, Maxwell, Boltzmann, Gibbs, and Feynman) has matched Newton’s combined achievements as theoretician, experimentalist, and mathematician. . . . If you were to become a time traveler and meet Newton on a trip back to the seventeenth century, you might find him something like the performer who first exasperates everyone in sight and then goes on stage and sings like an angel. . . .”

Perhaps more than any other scientist, Newton inspired the scientists who followed him with the idea that the universe could be understood in terms of mathematics. Journalist James Gleick writes, “Isaac Newton was born into a world of darkness, obscurity, and magic . . . veered at least once to the brink of madness . . . and yet discovered more of the essential core of human knowledge than anyone before or after. He was chief architect of the modern world. . . . He made knowledge a thing of substance: quantitative and exact. He established principles, and they are called his laws.”

Authors Richard Koch and Chris Smith note, “Some time between the 13th and 15th centuries, Europe pulled well ahead of the rest of the world in science and technology, a lead consolidated in the following 200 years. Then in 1687, Isaac Newton—foreshadowed by Copernicus, Kepler, and others—had his glorious insight that the universe is governed by a few physical, mechanical, and mathematical laws. This instilled tremendous confidence that everything made sense, everything fitted together, and everything could be improved by science.”

Inspired by Newton, astrophysicist Stephen Hawking writes, “I do not agree with the view that the universe is a mystery. . . . This view does not do justice to the scientific revolution that was started almost four hundred years ago by Galileo and carried on by Newton. . . . We now have mathematical laws that govern everything we normally experience.”

SEE ALSO Development of Modern Calculus (1665), Newton’s Prism (1672), Newton’s Laws of Motion and Gravitation (1687), Einstein as Inspiration (1921).

Photograph of Newton’s birthplace—Woolsthorpe Manor, England—along with an ancient apple tree. Newton performed many famous experiments on light and optics here. According to legend, Newton saw a falling apple here, which partly inspired his law of gravitation.

1687

Newton’s Laws of Motion and Gravitation • *Clifford A. Pickover*

Isaac Newton (1642–1727)

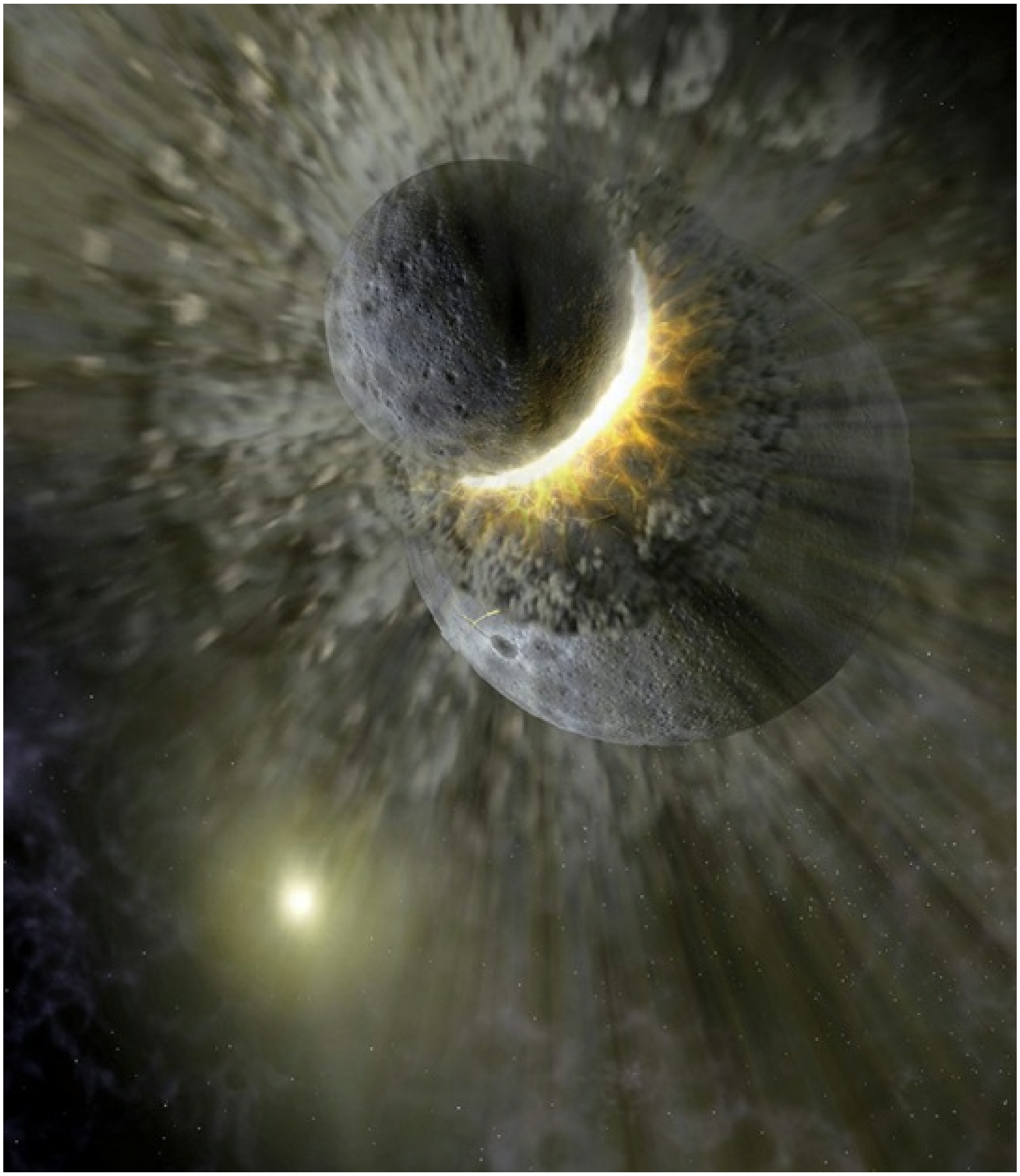
“God created everything by number, weight, and measure,” wrote Isaac Newton, the English mathematician, physicist, and astronomer who invented calculus, proved that white light was a mixture of colors, explained the rainbow, built the first reflecting telescope, discovered the binomial theorem, introduced polar coordinates, and showed the force causing objects to fall is the same kind of force that drives planetary motions and produces tides.

Newton’s Laws of Motion concern relations between forces acting on objects and the motion of these objects. His *Law of Universal Gravitation* states that objects attract one another with a force that varies as the product of the masses of the objects and inversely as the square of the distance between the objects. Newton’s *First Law of Motion* (*Law of Inertia*) states that bodies do not alter their motions unless forces are applied to them. A body at rest stays at rest. A moving body continues to travel with the same speed and direction unless acted upon by a net force. According to Newton’s *Second Law of Motion*, when a net force acts upon an object, the rate at which the momentum (mass × velocity) changes is proportional to the force applied. According to Newton’s *Third Law of Motion*, whenever one body exerts a force on a second body, the second body exerts a force on the first body that is equal in magnitude and opposite in direction. For example, the downward force of a spoon on the table is equal to the upward force of the table on the spoon.

Throughout his life, Newton is believed to have had bouts of manic depression. He had always hated his mother and stepfather, and as a teenager threatened to burn them alive in their house. Newton was also author of treatises on biblical subjects, including biblical prophecies. Few are aware that he devoted more time to the study of the Bible, theology, and alchemy than to science—and wrote more on religion than he did on natural science. Regardless, the English mathematician and physicist may well be the most influential scientist of all time.

SEE ALSO Kepler's Laws of Planetary Motion (1609), Acceleration of Falling Objects (1638), Development of Modern Calculus (1665), Newton's Prism (1672), Newton as Inspiration (1687), General Theory of Relativity (1915), Gravitational Lensing (1979).

Gravity affects the motions of bodies in outer space. Shown here is an artistic depiction of a massive collision of objects, perhaps as large as Pluto, that created the dust ring around the nearby star Vega.



1713

Law of Large Numbers • *Clifford A. Pickover*

Jacob Bernoulli (1654–1705)

In 1713, Swiss mathematician Jacob Bernoulli's proof of his Law of Large Numbers (LLN) was presented in a posthumous publication, *Ars Conjectandi* (*The Art of Conjecturing*). The LLN is a theorem in probability that describes the long-term stability of a random variable. For example, when the number of observations of an experiment (such as the tossing of a coin) is sufficiently large, then the proportion of an outcome (such as the occurrence of heads) will be close to the probability of the outcome, for example 0.5. Stated more formally, given a sequence of independent and identically distributed random variables with a finite population mean and variance, the average of these observations will approach the theoretical population mean.

Imagine you are tossing a standard six-sided die. We expect the mean of the values obtained by tossing to be the average, or 3.5. Imagine that your first three tosses happen to be 1, 2, and 6, giving a mean of 3. With more tosses, the value of the average eventually settles to the expected value of 3.5. Casino operators love the LLN because they can count on stable results in the long run and can plan accordingly. Insurers rely on the LLN to cope with and plan for variations in losses.

In *Ars Conjectandi*, Bernoulli estimates the proportion of white balls in an urn filled with an unknown number of black and white balls. By drawing balls from the urn and "randomly" replacing a ball after each draw, he estimates the proportion of white balls by the proportion of balls drawn that are white. By doing this enough times, he obtains any desired accuracy for the estimate. Bernoulli writes, "If observations of all events were to be continued throughout all eternity (and, hence, the ultimate probability would tend toward perfect certainty), everything in the world would be perceived to happen in fixed ratios. . . . Even in the most accidental . . . occurrences, we would be bound to recognize . . . a certain fate.”

SEE ALSO Dice (c. 3000 BCE), Normal Distribution Curve (1733), Bayes’ Theorem (1761), Laplace’s *Théorie Analytique des Probabilités* (1812).

Swiss commemorative stamp of mathematician Jacob Bernoulli, issued in 1994. The stamp features both a graph and a formula related to his Law of Large Numbers.

1727

Euler’s Number, *e* • *Clifford A. Pickover*

Leonhard Paul Euler (1707–1783)

British science writer David Darling writes that the number *e* is “possibly the most important number in mathematics. Although pi is more familiar to the layperson, *e* is far more significant and ubiquitous in the higher reaches of the subject.”

The number *e*, which is approximately equal to 2.71828, can be calculated in many ways. For example, it is the limit value of the expression $(1 + 1/n)$ raised to the nth power, when n increases indefinitely. Although mathematicians like Jacob Bernoulli and Gottfried Leibniz were aware of the constant, Swiss mathematician Leonhard Euler was among the first to extensively study the number, and he was the first to use the symbol *e* in letters written in 1727. In 1737, he showed that *e* is irrational—that is, it cannot be expressed as a ratio of two integers. In 1748, he calculated 18 of its digits, and today more than 100,000,000,000 digits of *e* are known.

e is used in diverse areas, such as in the formula for the catenary shape of a hanging rope supported at its two ends, in the calculation of compound interest, and in numerous applications in probability and statistics. It also appears in one of the most amazing mathematical relationships ever discovered, $e^{i\pi} + 1 = 0$, which unites the five most important symbols of mathematics: 1, 0, π, *e*, and *i* (the square root of minus one). Harvard mathematician Benjamin Pierce said that “we cannot understand [the formula], and we don’t know what it means, but we have proved it, and therefore we know it must be the truth.” Several surveys among mathematicians have placed this formula at the top of the list for the most beautiful formula in mathematics. Kasner and Newman note, “We can only reproduce the equation and not stop to inquire into its implications. It appeals equally to the mystic, the scientist, and the mathematician."

SEE ALSO π (c. 250 BCE) Imaginary Numbers (1572), Transcendental Numbers (1844).

The St. Louis Gateway Arch is in the shape of an upside-down catenary. A catenary can be described by the formula $y = (a/2)\cdot(e^{x/a} + e^{-x/a})$. *The Gateway Arch is the world's tallest monument, with a height of 630 feet (192 meters).*

1733

Normal Distribution Curve • *Clifford A. Pickover*

Abraham de Moivre (1667–1754), **Johann Carl Friedrich Gauss** (1777–1855), **Pierre-Simon Laplace** (1749–1827)

In 1733, French mathematician Abraham de Moivre was the first to describe the normal distribution curve, or law of errors, in *Approximatio ad summam terminorum binomii* $(a+b)^n$ *in seriem expansi* ("Approximation to the Sum of the Terms of a Binomial $(a+b)^n$ Expanded as a Series"). Throughout his life, de Moivre remained poor and earned money on the side by playing chess in coffeehouses.

The normal distribution—also called the Gaussian distribution, in honor of Carl Friedrich Gauss, who studied the curve years later—represents an important family of continuous probability distributions that are applied in countless fields in which observations are made. These fields include studies of population demographics, health statistics, astronomical measurements, heredity, intelligence, insurance statistics, and any fields in which variation exists in experimental data and observed characteristics. In fact, early in the eighteenth century, mathematicians began to realize that a vast number of different measurements tended to show a similar form of scattering or distribution.

The normal distribution is defined by two key parameters, the mean (or average) and the standard deviation, which quantifies the spread or variability of the data. The normal distribution, when graphed, is often called the *bell curve* because of its symmetric bell-like shape with values more concentrated in the middle than in the tails at the sides of the curve.

De Moivre researched the normal distribution during his studies of approximations to the binomial distribution, which arises, for example, in coin toss experiments. Pierre-Simon Laplace used the distribution in 1783 to study measurement errors. Gauss applied it in 1809 to study astronomical data.

The anthropologist Sir Francis Galton wrote of the normal distribution, "I know of scarcely anything so apt to impress the imagination as the wonderful form of cosmic order expressed by the 'Law of Frequency of Error.' The law would have been personified by the Greeks and deified, if they had known of it. It reigns with serenity and in complete self-effacement amidst the wildest confusion."

SEE ALSO Pascal's Triangle (1654), Law of Large Numbers (1713), Laplace's *Théorie Analytique des Probabilités* (1812)

A deutsche mark banknote featuring Carl Friedrich Gauss and a graph and formula of the normal probability function.


DEUTSCHE BUNDESBANK
Banknote
10
1777–1855 Carl Friedr. Gauß
AY7831976K1
10

1735

Linnaean Classification of Species •

Michael C. Gerald with Gloria E. Gerald

Aristotle (384–322 BCE), **Theophrastus** (372–287 BCE), **Carl Linnaeus** (1707–1778), **Charles Darwin** (1809–1882)

What do mountain lions, pumas, panthers, and catamonts have in common? These are but four of more than a dozen names given in the United States to the same animal, *Felis concolor*. When out and about in nature, we generally refer to plants and birds by their common names, but such names can be misleading. Crayfish, starfish, silverfish, and jellyfish are not related to each other and are not fish.

Classification goes back to ancient times. Aristotle grouped animals based on their mode of reproduction, while Theophrastus classified plants by their uses and methods of cultivation. In his first edition of *Systema Naturae* (1735), the Swedish botanist and physician Carl Linnaeus introduced a new approach to taxonomy (the science of naming and classifying plants and animals). First, he assigned latinized names to plants and animals, based on a binomial nomenclature (genus and species) that uniquely designated each living organism—a system that is still used. For example, the genus C*anis* includes the closely related dogs, wolves, coyotes, and jackals, with each unique member assigned a species name. Moreover, Linnaeus developed a multi-level hierarchical classification in which higher "ranks" would incorporate successive groups at lower levels. Related genera would be grouped into families—*Canis* and *Vulpes* (foxes) are grouped together in *Canidae*. Based on the Linnaean classification, the most inclusive rank was the kingdom, of which he counted two: animal and plant.

The Linnaean classification assigned organisms to different categories based on their physical characteristics and presumed natural relationships, and this was predicated on the then-prevailing Biblical interpretation that plants and animals were originally created in the form that they now exist. One century later, Darwin presented convincing evidence that two extant animals or plants might have had a common ancestor or that extinct organisms may have been the ancestors of those extant. Contemporary classifications are based on phylogenetic systematics, which incorporates relationships that include both extant and extinct organisms.

SEE ALSO Fossil Record and Evolution (1836), Darwin's Theory of Natural Section (1859), Domains of Life (1990).

A signboard of Methodus plantarum sexualis (1736), a work by Georg Dionysius Ehret (1708–1770), a German botanist best known for his botanical illustrations. This image depicts the twenty-four classes of plant sexual systems devised by Linnaeus.


Clariss: LINNÆI. M. D.
METHODUS plantarum SEXUALIS
in SISTEMATE NATURÆ
descripta
A B C D
E F G H
I K L M
N O P Q
R S T U
V X Y Z
Lugd. bat: 1736
G.D. EHRET. Palat-heidelb:
fecit & edidit
Monandria.
Diandria.
Triandria.
Tetrandria.
Pentandria.
Hexandria.
Heptandria.
Octandria.
Enneandria.
Decandria.
Dodecandria
Icosandria
Polyandria
Didynamia
Tetradinamia.
Monadelphia.
Diadelphia.
Polyadelphia.
Syngenesia.
Gynandria.
Monoecia.
Dioecia.
Polygamia.
Cryptogamia.

1738

Bernoulli’s Law of Fluid Dynamics •

Clifford A. Pickover

Daniel Bernoulli (1700–1782)

Imagine water flowing steadily through a pipe that carries the liquid from the roof of a building to the grass below. The pressure of the liquid will change along the pipe. Mathematician and physicist Daniel Bernoulli discovered the law that relates pressure, flow speed, and height for a fluid flowing in a pipe. Today, we write Bernoulli’s Law as $v^2/2 + gz + p/\rho = C$. Here, v is the fluid velocity, g the acceleration due to gravity, z the elevation (height) of a point in the fluid, p the pressure, ρ the fluid density, and C is a constant. Scientists prior to Bernoulli had understood that a moving body exchanges its kinetic energy for potential energy when the body gains height. Bernoulli realized that, in a similar way, changes in the kinetic energy of a moving fluid result in a change in pressure.

The formula assumes a steady (non-turbulent) fluid flow in a closed pipe. The fluid must be incompressible. Because most liquid fluids are only slightly compressible, Bernoulli’s Law is often a useful approximation. Additionally, the fluid should not be viscous, which means that the fluid should not have internal friction. Although no real fluid meets all these criteria, Bernoulli’s relationship is generally very accurate for free flowing regions of fluids that are away from the walls of pipes or containers, and it is especially useful for gases and light liquids.

Bernoulli’s Law often makes reference to a subset of the parameters in the above equation, namely that the decrease in pressure occurs simultaneously with an increase in velocity. The law is used when designing a *venturi throat*

—a constricted region in the air passage of a carburetor that causes a reduction in pressure, which in turn causes fuel vapor to be drawn out of the carburetor bowl. The fluid increases speed in the smaller-diameter region, reducing its pressure and producing a partial vacuum via Bernoulli's Law.

Bernoulli's formula has numerous practical applications in the fields of aerodynamics, where it is considered when studying flow over airfoils, such as wings, propeller blades, and rudders.

SEE ALSO Archimedes Principle of Buoyancy (c. 250 BCE), Brownian Motion (1827), Wright Brothers' Airplane (1903)

Many engine carburetors have contained a venturi with a narrow throat region that speeds the air and reduces the pressure to draw fuel via Bernoulli's Law. The venture throat is labeled 10 in this 1935 carburetor patent.

April 9, 1935. C. N. POGUE 1,997,497

CARBURETOR

Filed Nov. 3, 1934 2 Sheets-Sheet 2

Fig. 3

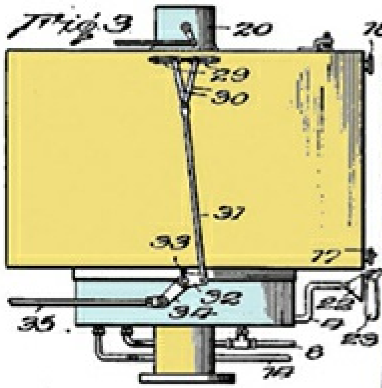


Fig. 5.

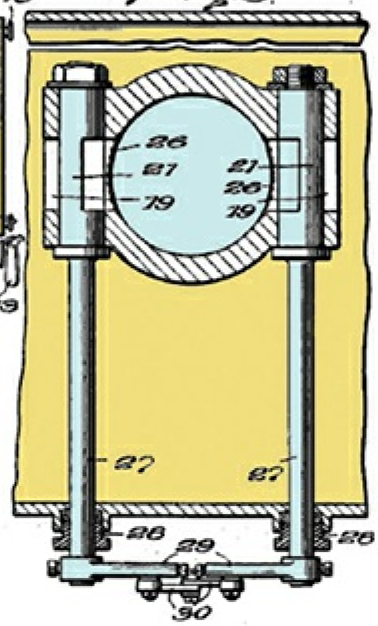


Fig. 4.

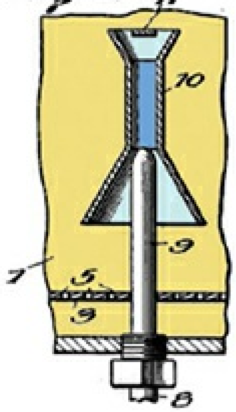


Fig. 7.

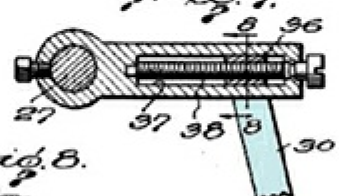


Fig. 8.

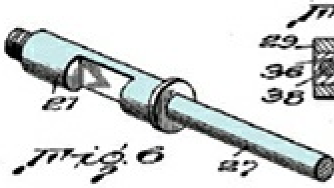


Fig. 6

Inventor

Charles N. Pogue

By Pennie Davis Marvin & Edmonds

Attorneys

1760

Artificial Selection (Selective Breeding) • *Michael C. Gerald with Gloria E. Gerald*

Abu Rayhan Biruni (973–1048), **Robert Bakewell** (1725–1795), **Charles Darwin** (1809–1882)

A fundamental building block Charles Darwin used in conceptualizing his theory of natural selection was selective breeding, and he specifically cited the pioneering work of Robert Bakewell in this field. Darwin noted that many domesticated animals and plants were developed by intentionally breeding individuals with special prized traits.

Selective breeding, a term coined by Darwin, was practiced by the Romans 2,000 years ago and was described by the Persian polymath Abu Rayhan Biruni during the eleventh century. However, it was Bakewell, a leading figure during the British Agricultural Revolution, who introduced it on a scientific basis. Bakewell was born into a family of English tenant farmers and spent his early years traveling on the Continent, learning farming methods. Upon his father's death in 1760, he took control of the farm and transformed its grasslands for cattle grazing by using his innovative breeding techniques, irrigation, flooding, and fertilizing pasturelands. He then turned his attention to livestock and, through selective breeding, produced the New Leichester sheep lineage. Characterized as large and fine boned, this breed's long lustrous wool was extensively exported to North America and Australia. Today, Bakewell's legacy is not his breeds but his breeding methods.

Desirable traits are specific to the species being bred, and individual members are crossbred to obtain a hybridized product with these characteristics. Plants are commonly bred for high crop yields, a fast growth rate, and resistance to disease and negative climatic conditions. For chickens, breeding objectives might include the quality and size of the eggs, the meat, and the production of young birds likely to successfully reproduce. Aquaculture, involving fish and shellfish, has yet to achieve its full potential. Breeding objectives include an increase in growth and survival rates, meat quality, and resistance to disease, and for shellfish, also shell size and color.

SEE ALSO Wheat: The Staff of Life (c. 11,000 BCE), Agriculture (c. 10,000 BCE), Rice Cultivation (c. 7000 BCE) Darwin's Theory of Natural Section (1859).

A champion bull is being led in the ring at an agricultural show in Scotland, perhaps anticipating another blue ribbon to add to his collection.

1761

Bayes' Theorem • *Clifford A. Pickover*

Thomas Bayes (c. 1702–1761)

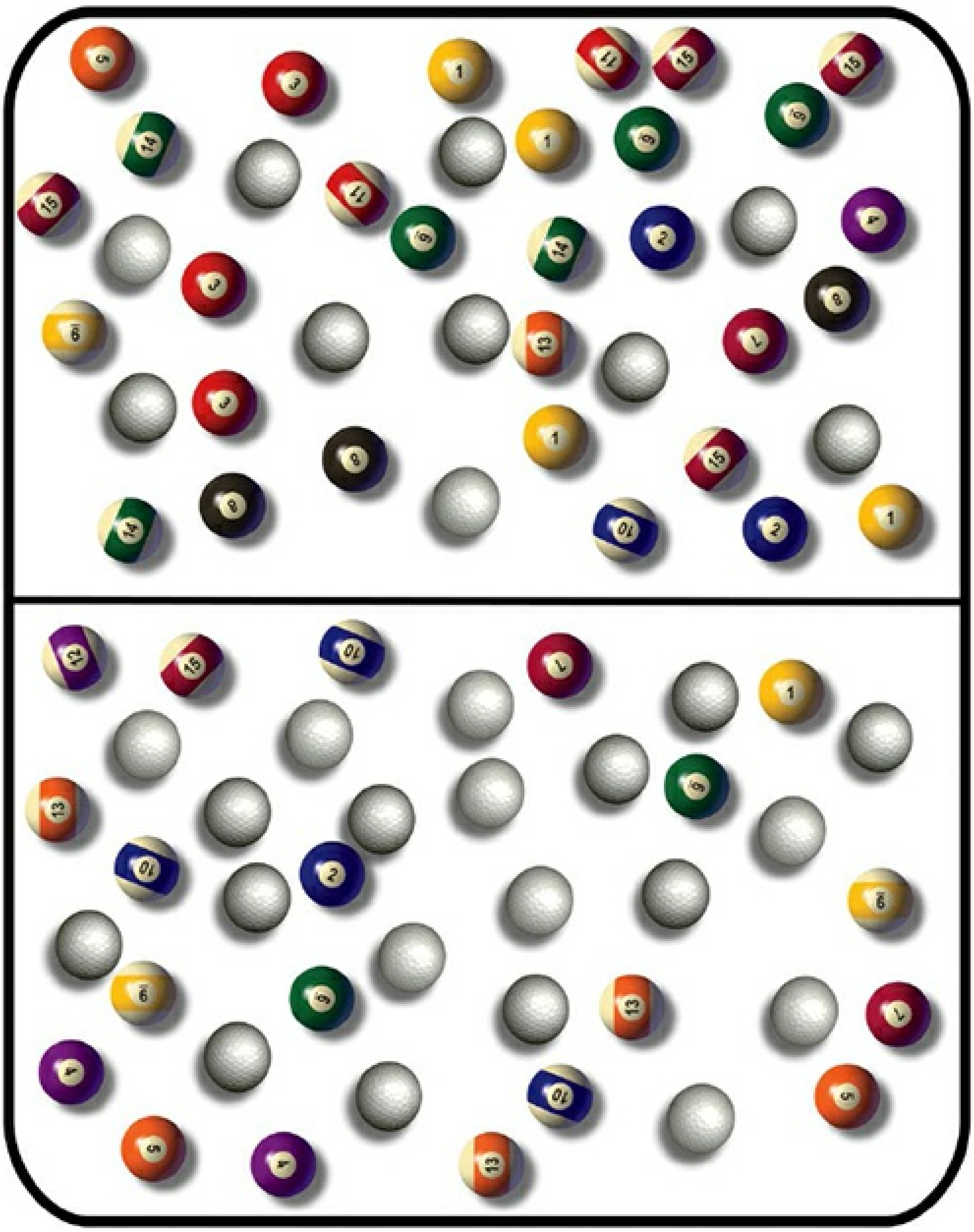
Bayes' theorem, formulated by British mathematician and Presbyterian minister Thomas Bayes, plays a fundamental role in science and can be stated by a simple mathematical formula used for calculating conditional probabilities. *Conditional probability* refers to the probability of some event A, given the occurrence of some other event B, written as $P(A|B)$. Bayes' theorem states: $P(A|B) = [P(B|A) \times P(A)]/P(B)$. Here, $P(A)$ is called the prior probability of A because it is the probability of event A without taking into account anything we know about B. $P(B|A)$ is the conditional probability of B given A. $P(B)$ is the prior probability of B.

Imagine we have two boxes. Box 1 has 10 golf balls and 30 billiard balls. Box 2 has 20 of each. You select a box at random and pull out a ball. We assume that the balls are equally likely to be selected. Your ball turns out to be a billiard ball. How probable is it that you chose Box 1? In other words, what is the probability that you chose Box 1, given that you have a billiard ball in your hand?

Event A corresponds to your picking Box 1. Event B is your picking a billiard ball. We want to compute $P(A|B)$. $P(A)$ is 0.5, or 50 percent. $P(B)$ is the probability of picking a billiard ball regardless of any information on the boxes. It is computed as the sum of the probability of getting a billiard ball from a box multiplied by the probability of selecting a box. The probability of picking a billiard ball from Box 1 is 0.75. The probability of picking one from Box 2 is 0.5. The probability of getting a billiard ball overall is $0.75 \times 0.5 + 0.5 \times 0.5 = 0.625$. $P(B|A)$, or the probability of getting a billiard ball given that you selected Box 1, is 0.75. We can use Bayes' formula to find that the probability of your having chosen Box 1, which is $P(A|B) = 0.6$.

SEE ALSO Aristotle's *Organon* (c. 350 BCE), Law of Large Numbers (1713), Laplace's *Théorie Analytique des Probabilités* (1812).

Box 1 (upper box) and Box 2 (lower box) are shown here. You select a box at random and withdraw a billiard ball. How probable it is that you choose the upper box?



1761

Causes of Cancer • *Clifford A. Pickover*

Bernardino Ramazzini (1633–1714), **John Hill** (1707–1775), **Sir Percivall Pott** (1714–1788), **Heinrich Wilhelm Gottfried von Waldeyer-Hartz** (1836–1921), **Katsusaburo Yamagiwa** (1863–1930)

Journalist John Bloom writes, "If the body's cells represent a kind of Plato's republic of somatic harmony—[the cells] each doing a specific job in precise proportion to every other cell—then cancer cells represent guerilla soldiers bent on a coup d'état." Cancer refers to a group of diseases in which cells exhibit uncontrolled growth and sometimes metastasis (spreading to other areas of the body). Cancers are caused by abnormalities in the genetic material of cells and have many possible causes, including carcinogens (e.g., tobacco smoke, sunlight, or viruses) and random errors in DNA replication.

Among the earliest documented cases of probable cancer are described in an Egyptian papyrus, c. 1600 BCE, involving eight cases of tumors in the breast. These tumors were treated by cauterization using a hot device called "the fire drill."

In 1713, Italian physician Bernardino Ramazzini reported on the virtual absence of cervical cancer in nuns when compared with married woman, speculating that sexual intercourse may increase cancer risk. The first paper describing a relationship between use of tobacco snuff and nasal cancer was published by English physician John Hill in 1761, after his startling discovery that his patients were all snuff users. He suggested, more generally, that substances in the environment may promote cancer. In 1775, another English physician, Percivall Pott, attributed high incidences of cancer of the scrotum among chimney sweeps to their contact with coal soot. He even recorded the cancer of a young boy who had been an apprentice to a chimney sweep. Finally, in 1915, Japanese researcher Katsusaburo Yamagiwa showed that frequent painting of rabbits' skins with coal tar did indeed induce cancer.

Note that in the 1860s, the German anatomist Wilhelm von Waldeyer-Hartz classified various kinds of cancer cells and suggested that cancer begins in a single cell and may spread through the blood or lymphatic system. Today, we know that tumor-suppressor genes, which normally inhibit uncontrolled cell division, may be inactivated by genetic changes associated with cancers.

SEE ALSO Cell Division (1855), HeLa Cells (1951), Epigenetics (1983), Telomerase (1984).

Two views of Clara Jacobi, a Dutch woman who had a tumor removed from her neck in 1689.

1761

Morgagni’s “Cries of Suffering Organs” • *Clifford A. Pickover*

Andreas Vesalius (1514–1564), **Gabriele Falloppio** (1523–1562), **Giovanni Battista Morgagni** (1682–1771), **Marie François Xavier Bichat** (1771–1802), **Rudolf Ludwig Karl Virchow** (1821–1902)

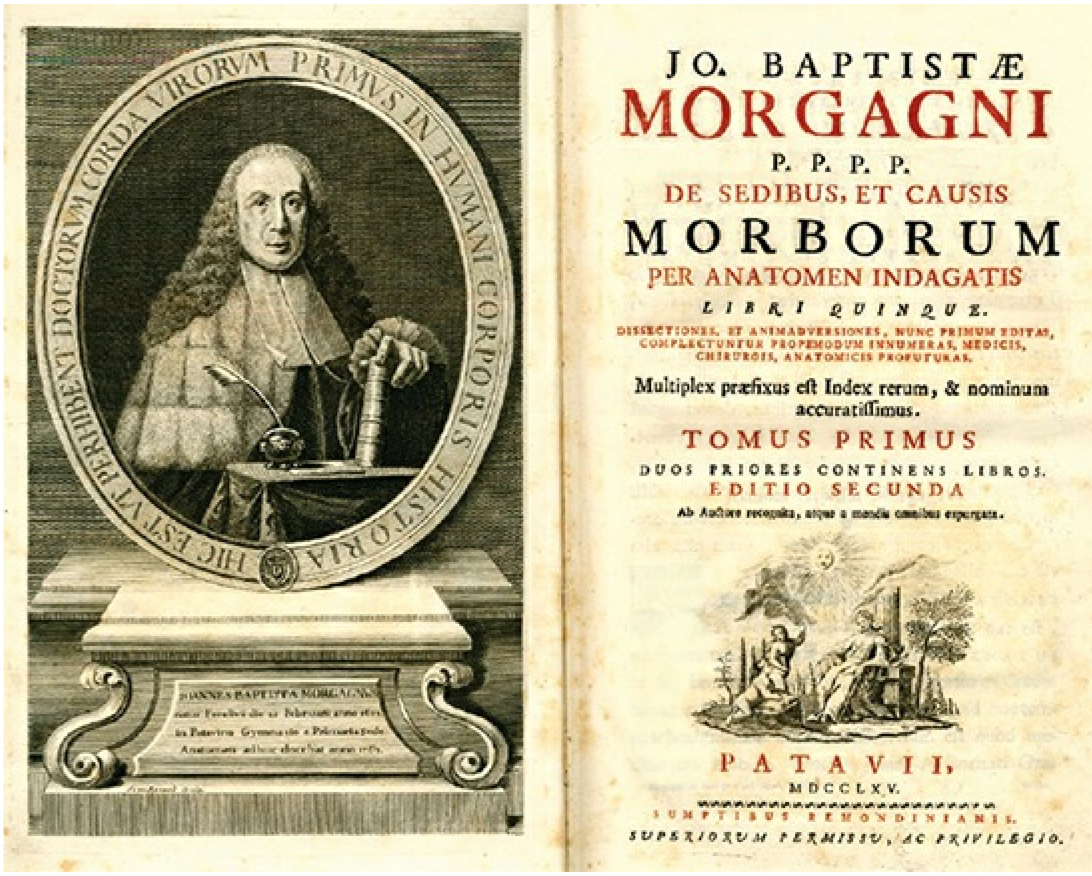
“The idea that symptoms of disease, from colds to cancer, arise from changes in organs and tissues of the body seems commonplace if not banal,” writes author John G. Simmons. “But the systematic correlation of the clinical history of disease with structural changes seen at autopsy was once a novel concept.” With the 1761 publication of Italian anatomist Giovanni Morgagni’s monumental work, *De sedibus et causis morborum per anatomen indagatis (On the Seats and Causes of Disease)*, Morgagni became the father of modern anatomical pathology, the diagnosis of disease based on examination of bodies, organs, and tissues. For Morgagni, disease symptoms were the “cries of suffering organs.”

Although other researchers such as Andreas Vesalius and Gabriele Falloppio had performed extensive anatomical studies, Morgagni’s work was notable in its accurate and systematic examinations of diseased organs and parts. *De sedibus*, published when Morgagni was 79 years old, records roughly 650 dissections. During clinical practice, Morgagni made careful observations of a patient’s illness and then attempted to identify the underlying causes upon autopsy. In conducting his research, he essentially debunked the ancient humoral theory of diseases, which posited an imbalance in bodily fluids as the root of disease. *De sedibus* identifies pathologies such as hepatic cirrhosis (a chronic degenerative disease in which normal liver cells are damaged and replaced by scar tissue), syphilitic lesions of the brain, stomach cancers and ulcers, and diseases of heart valves. Morgagni also observed that a lesion on one side of the brain, causing a stroke, led to paralysis of the other side of the body.

So immersed was Morgagni in his work that in old age he remarked, “I have passed my life amidst books and cadavers.” Later, French anatomist Marie Bichat contributed to the field of pathology by identifying many kinds of body tissues and the effect of diseases on tissues. In the 1800s, the German pathologist Rudolf Virchow contributed to cellular pathology and was the first to recognize the effect of leukemia on blood cells.

SEE ALSO *De Humani Corporis Fabrica* (1543), Cerebral Localization (1861), Brain Lateralization (1964).

Frontispiece and title page of Giovanni Morgagni’s De sedibus.



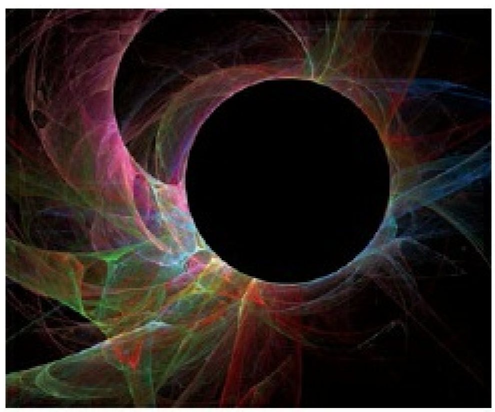
JO. BAPTISTÆ
MORGAGNI
P. P. P. P.
DE SEDIBUS, ET CAUSIS
MORBORUM
PER ANATOMEN INDAGATIS
LIBRI QUINQUE.
DISSECTIONES, ET ANIMADVERSIONES, NUNC PRIMUM EDITAS, COMPLECTUNTUR PROPEMODUM INNUMERAS, MEDICIS, CHIRURGIS, ANATOMICIS PROFUTURAS.
Multiplex præfixus est Index rerum, & nominum accuratissimus.
TOMUS PRIMUS
DUOS PRIORES CONTINENS LIBROS.
EDITIO SECUNDA
Ab Auctore recognita, atque a mendis omnibus expurgata.

PATAVII,
MDCCLXV.
SUMPTIBUS REMONDINIANIS.
SUPERIORUM PERMISSU, AC PRIVILEGIO.

1783

Black Holes • *Clifford A. Pickover*

John Michell (1724–1793), **Karl Schwarzschild** (1873–1916), **John Archibald Wheeler** (1911–2008), **Stephen William Hawking** (1942–2018)



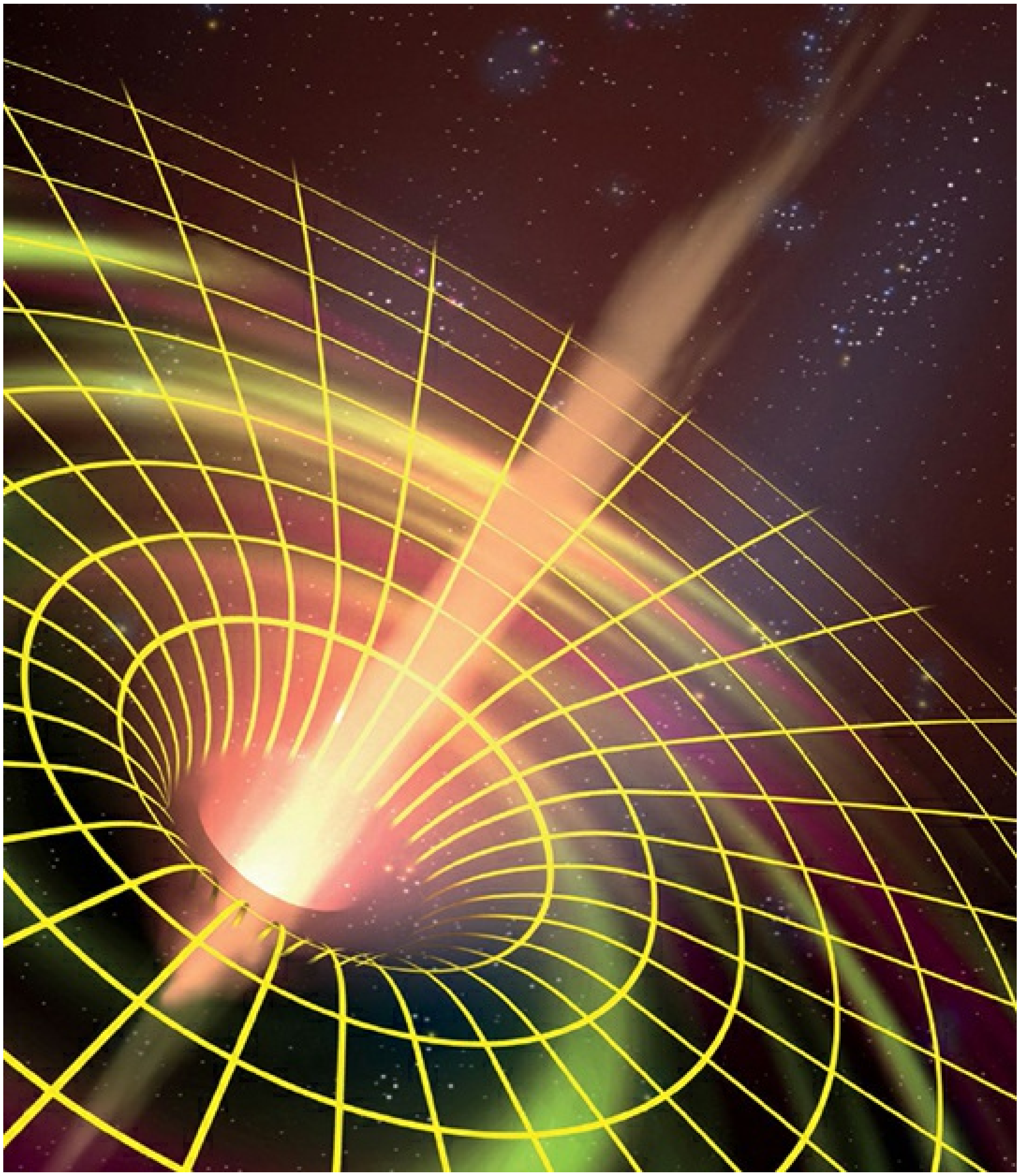
Astronomers may not believe in Hell, but most believe in ravenous, black regions of space in front of which one would be advised to place a sign, “Abandon hope, all ye who enter here.” This was Italian poet Dante Alighieri’s warning when describing the entrance to the Inferno in his *Divine Comedy*, and, as astrophysicist Stephen Hawking has suggested, this would be the appropriate message for travelers approaching a black hole.

These cosmological hells truly exist in the centers of many galaxies. Such galactic black holes are collapsed objects having millions or even billions of times the mass of our Sun crammed into a space no larger than our Solar System. According to classical black hole theory, the gravitational field around such objects is so great that nothing—not even light—can escape from their tenacious grip. Anyone who falls into a black hole will plunge into a tiny central region of extremely high density and extremely small volume . . . and the end of time. When quantum theory is considered, black holes are thought to emit a form of radiation called Hawking radiation (see “Notes and Further Reading”).

Black holes can exist in many sizes. As some historical background, just a few weeks after Albert Einstein published his general relativity theory in 1915, German astronomer Karl Schwarzschild performed exact calculations of what is now called the Schwarzschild radius, or event horizon. This radius defines a sphere surrounding a body of a particular mass. In classical black-hole theory, within the sphere of a black hole, gravity is so strong that no light, matter, or signal can escape. For a mass equal to the mass of our Sun, the Schwarzschild radius is a few kilometers in length. A black hole with an event horizon the size of a walnut would have a mass equal to the mass of the Earth. The actual concept of an object so massive that light could not escape was first suggested in 1783 by the geologist John Michell. The term “black hole” was coined in 1967 by theoretical physicist John Wheeler.

SEE ALSO Sun-Centered Universe (1543), Telescope (1608), Main Sequence (1910), General Theory of Relativity (1915), Neutron Star (1933), Stellar Nucleosynthesis (1946), Gravitational Lensing (1979), Gravitational Waves (2016).

LEFT: *Black holes and Hawking radiation are the stimulus for numerous impressionistic pieces by Slovenian artist Teja Krašek.* RIGHT: *Artistic depiction of the warpage of space in the vicinity of a black hole.*



1785

Coulomb's Law of Electrostatics •

Clifford A. Pickover

Charles-Augustin Coulomb (1736–1806)

"We call that fire of the black thunder-cloud *electricity*," wrote essayist Thomas Carlyle in the 1800s, "but what is it? What made it?" Early steps to understand electric charge were taken by French physicist Charles-Augustin Coulomb, the preeminent physicist who contributed to the fields of electricity, magnetism, and mechanics. His Law of Electrostatics states that the force of attraction or repulsion between two electric charges is proportional to the product of the magnitude of the charges and inversely proportional to the square of their separation distance *r*. If the charges have the same sign, the force is repulsive. If the charges have opposite signs, the force is attractive.

Today, experiments have demonstrated that Coulomb's Law is valid over a remarkable range of separation distances, from as small as 10^{-16} meters (a tenth of the diameter of an atomic nucleus) to as large as 10^6 meters (where 1 meter is equal to 3.28 feet). Coulomb's Law is accurate only when the charged particles are stationary because movement produces magnetic fields that alter the forces on the charges.

Although other researchers before Coulomb had suggested the $1/r^2$ law, we refer to this relationship as Coulomb's Law in honor of Coulomb's independent results gained through the evidence provided by his torsional measuring. In other words, Coulomb provided convincing quantitative results for what was, up to 1785, just a good guess.

One version of Coulomb's torsion balance contains a metal and a nonmetal ball attached to an insulating rod. The rod is suspended at its middle by a nonconducting filament or fiber. To measure the electrostatic force, the metal ball is charged. A third ball with similar charge is placed near the charged ball of the balance, causing the ball on the balance to be repelled. This repulsion causes the fiber to twist. If we measure how much force is required to twist the wire by the same angle of rotation, we can estimate the degree of force caused by the charged sphere. In other words, the fiber acts as a very sensitive spring that supplies a force proportional to the angle of twist.

SEE ALSO Von Guericke's Electrostatic Generator (1660), Battery (1800), Maxwell's Equations (1861), Electron (1897).

Charles-Augustin de Coulomb's torsion balance, from his Mémoires sur l'électricité et le magnétisme (1785–1789).

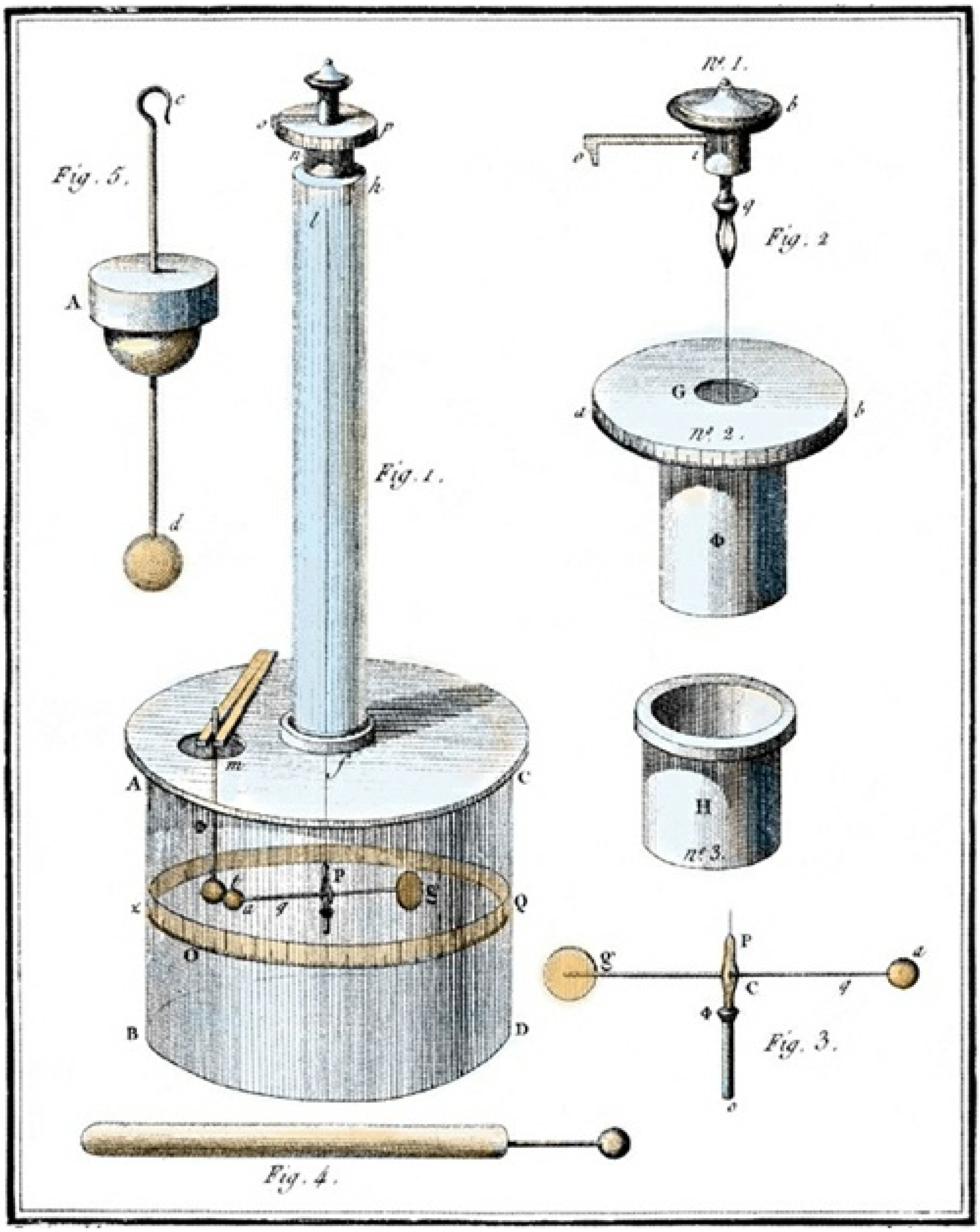


Fig. 5.
Fig. 1.
Fig. 2
Fig. 3.
Fig. 4.
nº 1.
nº 2.
nº 3.

1797

Fundamental Theorem of Algebra •

Clifford A. Pickover

Johann Carl Friedrich Gauss (1777–1855)

The Fundamental Theorem of Algebra (FTA) is stated in several forms, one of which is that every polynomial of degree $n \geq 1$, with real or complex coefficients, has n real or complex roots. In other words, a polynomial $P(x)$ of degree n has n values x_i (some of which are possibly repeated) for which $P(x_i) = 0$. As background, polynomial equations of degree n are of the form $P(x) = a_n x^n + a_{n-1} x^{n-1} + \ldots + a_1 x + a_0 = 0$ where $a_n \neq 0$.

As an example, consider the quadratic polynomial $f(x) = x^2 - 4$. When plotted, the curve is a parabola with its minimum at $f(x) = -4$. The polynomial has two distinct real roots ($x = 2$ and $x = -2$), which are graphically seen as points where the parabola intersects the x-axis. .

This theorem is notable, in part, because of the sheer number of attempts at proving it through history. German mathematician Carl Friedrich Gauss is usually credited with the first proof of the FTA, discovered in 1797. In his doctoral thesis, published in 1799, he presented his first proof, which focused on polynomials with real coefficients, and also on his objections to the other previous attempts at proofs. By today's standards, Gauss's proof was not rigorously complete, because he relied on the continuity of certain curves, but it was a significant improvement over all previous attempts at a proof.

Gauss considered the FTA to have great importance, as evidenced by his returning to the problem repeatedly. His fourth proof was in the last paper he ever wrote, which appeared in 1849, exactly 50 years after his dissertation. Note that Jean-Robert Argand (1768–1822) published a rigorous proof of the

Fundamental Theorem of Algebra in 1806 for polynomials with complex coefficients. The FTA arises in many areas of mathematics, and the various proofs span fields that range from abstract algebra and complex analysis to topology.

SEE ALSO al-Khwarizmi's *Algebra* (830), Development of Modern Calculus (1665), Fractals (1975).

Greg Fowler's depiction of the three solutions to $z^3 - 1 = 0$*. These roots (or zeros) are 1,* $-0.5 + 0.86603i$*, and* $-0.5 - 0.86603i$*, and are located at the center of the three large bull's-eyes in this Newton's method rendition of the solutions.*

1798

Smallpox Vaccine • *Clifford A. Pickover*

Edward Anthony Jenner (1749–1823)

“Smallpox is a disease that terrified people for thousands of years,” writes medical historian Robert Mulcahy. “During the 1700s, this disease took approximately 400,000 lives each year in Europe alone and left hundreds of thousands more living with scarred and disfigured faces. The smallpox virus could spread through a town like wildfire, bringing high fever and a blistering rash to everyone who caught it. Half of those who contracted the disease would die within weeks—and there was no cure.”

Smallpox is a contagious viral disease that has devastated populations since the dawn of humanity. Smallpox skin lesions have even been found on the faces of ancient Egyptian mummies (c. 1100 BCE). When Europeans introduced the disease to the New World, smallpox became instrumental in the fall of the Aztec and Incan empires.

For many years, English physician Edward Jenner had heard tales that dairymaids were protected from smallpox after they had been afflicted with cowpox, a similar disease that affects cows but is not fatal for humans. In 1796, he removed material from a dairymaid’s cowpox lesions and transferred it into two scratches he made in the skin of an eight-year-old boy. The boy developed a minor fever and discomfort but soon was completely recovered. Later, Jenner inoculated the boy with material from a smallpox lesion, and no disease developed in the boy. In 1798, Jenner published additional findings in *An Inquiry into the Causes and Effects of the Variolae Vaccinae.* He called the procedure vaccination—which stems from *vacca,* the Latin word for cow—and began to send cowpox vaccine samples to anyone who requested them.

Jenner was not the first to vaccinate against smallpox. However, his work is considered among the first *scientific* attempts to control infectious disease. Physician Stefan Riedel writes that it was Jenner's "relentless promotion and devoted research of vaccination that changed the way medicine was practiced." Eventually, the smallpox vaccination was used throughout the world. By 1979 the world was essentially free of smallpox, and routine vaccination was no longer needed.

SEE ALSO Germ Theory of Disease (1862), Discovery of Viruses (1892), Structure of Antibodies (1959).

An 1802 cartoon by British satirist James Gillray, depicting the early controversy surrounding Jenner's vaccination theory. Note the cows emerging from the people's bodies.

1800

Battery • *Clifford A. Pickover*

Luigi Galvani (1737–1798), **Alessandro Volta** (1745–1827), **Gaston Planté** (1834–1889)

Batteries have played an invaluable role in the history of physics, chemistry, and industry. As batteries evolved in power and sophistication, they facilitated important advances in electrical applications, from the emergence of telegraph communication systems to their use in vehicles, cameras, computers, and phones.

Around 1780, physiologist Luigi Galvani experimented with frogs' legs that he could cause to jerk when in contact with metal. Science-journalist Michael Guillen writes, "During his sensational public lectures, Galvani showed people how dozens of frogs' legs twitched uncontrollably when hung on copper hooks from an iron wire, like so much wet laundry strung out on a clothesline. Orthodox science cringed at his theories, but the spectacle of that chorus line of flexing frog legs guaranteed Galvani sell-out crowds in auditoriums the world over." Galvani ascribed the leg movement to "animal electricity." However, Italian physicist and friend Alessandro Volta believed that the phenomenon had more to do with the different metals Galvani employed, which were joined by a moist connecting substance. In 1800, Volta invented what has been traditionally considered to be the first electric battery when he stacked several pairs of alternating copper and zinc discs separated by cloth soaked in salt water. When the top and bottom of this *voltaic pile* were connected by a wire, an electric current began to flow. To determine that current was flowing, Volta could touch its two terminals to his tongue and experience a tingly sensation.

“A battery is essentially a can full of chemicals that produce electrons,” write authors Marshall Brain and Charles Bryant. If a wire is connected between the negative and positive terminals, the electrons produced by chemical reactions flow from one terminal to the other.

In 1859, physicist Gaston Planté invented the rechargeable battery. By forcing a current through it “backwards,” he could recharge his lead-acid battery. In the 1880s, scientists invented commercially successful dry cell batteries, which made use of pastes instead of liquid electrolytes (substances containing free ions that make the substances electrically conductive).

SEE ALSO Von Guericke’s Electrostatic Generator (1660), Power Grid (1878), Electron (1897).

As batteries evolved, they facilitated important advances in electrical applications, ranging from the emergence of telegraph communication systems to their use in vehicles, cameras, computers, and phones.

1800

High-Pressure Steam Engine • *Marshall Brain*

Richard Trevithick (1771–1833)

There was a time in history when the human body was the only way to power things. Then we learned to harness horses and oxen. Then we figured out how to use water for power with waterwheels. But all these sources of power have their limitations. You cannot create a locomotive or a cruise ship like the *Titanic* with any of these power sources. And while you can create a power plant or a factory powered by water, you are severely limited as to where you can locate them. The world needed a better source of power.

The steam engine provided the transition to the industrial age. The first high-pressure steam engine was introduced in 1800 by British engineer Richard Trevithick. By 1850, engineers had incrementally improved steam engines and the Corliss steam engine became the state of the art for large stationary power needs. It was efficient and reliable, as well as large and heavy, making it a good engine for powering factories. The San Francisco cable car system used steam engines of this type.

The engine used to power the Centennial Exhibition in Philadelphia in 1876 is an example: a two-cylinder steam engine producing 1,400 horsepower (one million watts). Pistons more than a yard (one meter) in diameter moved 10 feet (3 meters) in their cylinders to spin a flywheel 30 feet (9 meters) across.

The *Titanic* used the next generation of steam engine, in which multiple cylinders captured energy from successive expansions of the same steam.

A key element for any high-pressure steam engine is the boiler, where boiling water creates the steam pressure. The problem with boilers is that, being under high pressure, they had some probability of exploding. One of the most horrific boiler explosions occurred aboard a steam-powered ship named the Sultana in 1865. It had four boilers, one of which had started leaking and had been hastily repaired. With roughly 2,000 people on board, the repaired area presumably failed, causing an immense boiler explosion that killed a total of about 1,800 people. Today engineers spec steam turbines instead. You find them in nearly every power plant.

SEE ALSO Carnot Engine (1824), Steam Turbine (1890), Internal Combustion Engine (1908).

President Ulysses S. Grant and Don Pedro starting the Corliss engine at the Centennial celebration, Philadelphia, 1876.

1801

Wave Nature of Light • *Clifford A. Pickover*

Christiaan Huygens (1629–1695), **Isaac Newton** (1642–1727), **Thomas Young** (1773–1829)

"What is light?" is a question that has intrigued scientists for centuries. In 1675, the famous English scientist Isaac Newton proposed that light was a stream of tiny particles. His rival, the Dutch physicist Christiaan Huygens, suggested that light consisted of waves, but Newton's theories often dominated, partly due to Newton's prestige.

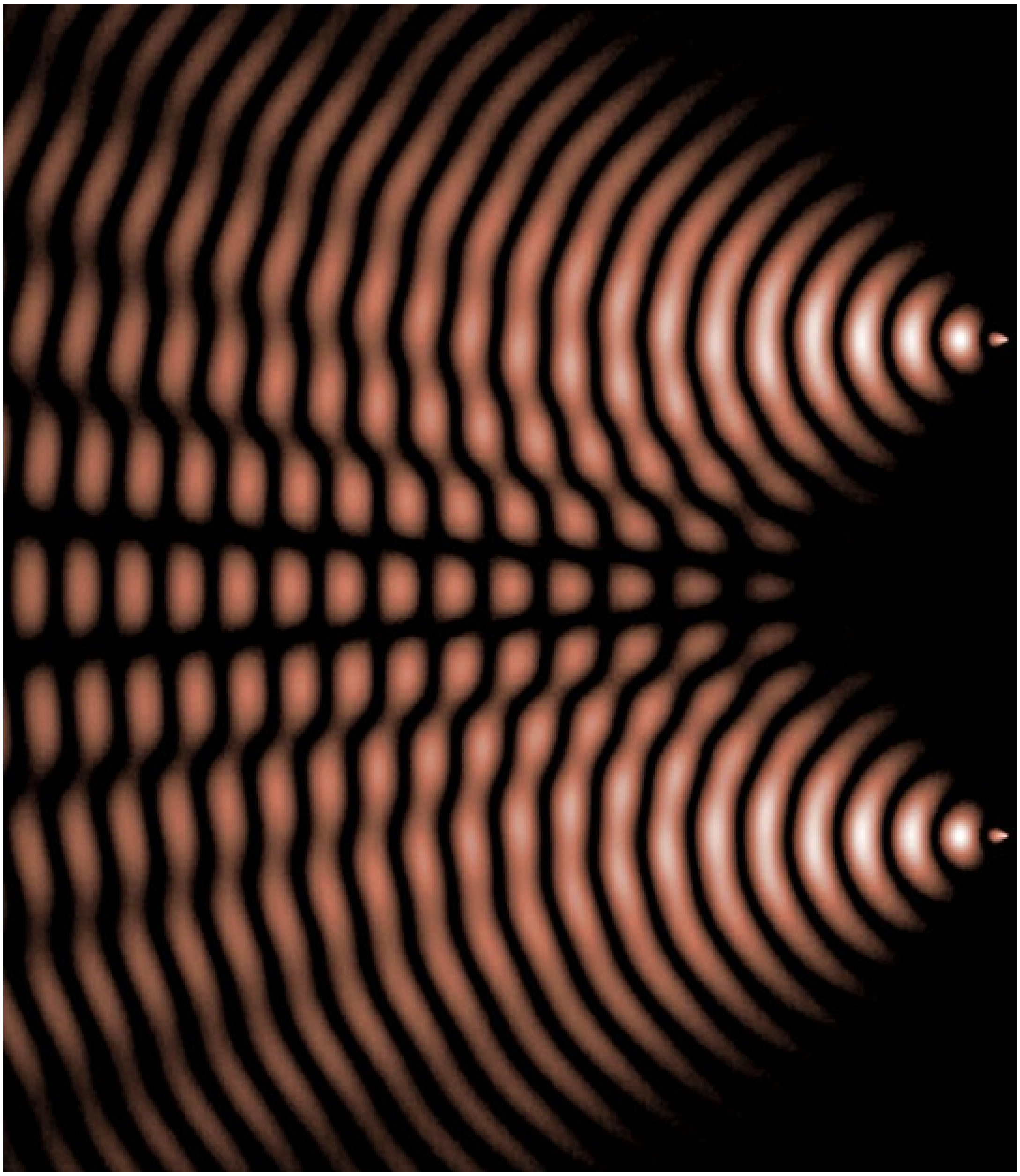
Around 1800, the English researcher Thomas Young—also famous for his work on deciphering the Rosetta Stone—began a series of experiments that provided support for Huygens' wave theory. In a modern version of Young's experiment, a laser equally illuminates two parallel slits in an opaque surface. The pattern that the light makes as it passes through the two slits is observed on a distant screen. Young used geometrical arguments to show that the superposition of light waves from the two slits explains the observed series of equally spaced bands (fringes) of light and dark regions, representing constructive and destructive interference, respectively. You can think of these patterns of light as being similar to the tossing of two stones into a lake and watching the waves running into one another and sometimes canceling each other out or building up to form even larger waves.

If we carry out the same experiment with a beam of electrons instead of light, the resulting interference pattern is similar. This observation is intriguing, because if the electrons behaved only as particles, one might expect to simply see two bright spots corresponding to the two slits.

Today, we know that the behavior of light and subatomic particles can be even more mysterious. When single electrons are sent through the slits one at a time, an interference pattern is produced that is similar to that produced for waves passing through both holes at once. This behavior applies to all subatomic particles, not just photons (light particles) and electrons, and suggests that light and other subatomic particles have a mysterious combination of particle and wavelike behavior, which is just one aspect of the quantum mechanics revolution in physics.

SEE ALSO Maxwell's Equations (1861), Electromagnetic Spectrum (1864), Electron (1897), Photoelectric Effect (1905), De Broglie Relation (1924), Schrödinger's Wave Equation (1926), Complementarity Principle (1927).

Simulation of the interference between two point sources. Young showed that the superposition of light waves from two slits explains the observed series of bands of light and dark regions, representing constructive and destructive interference, respectively.



1807

Fourier Series • *Clifford A. Pickover*

Jean Baptiste Joseph Fourier (1768–1830)

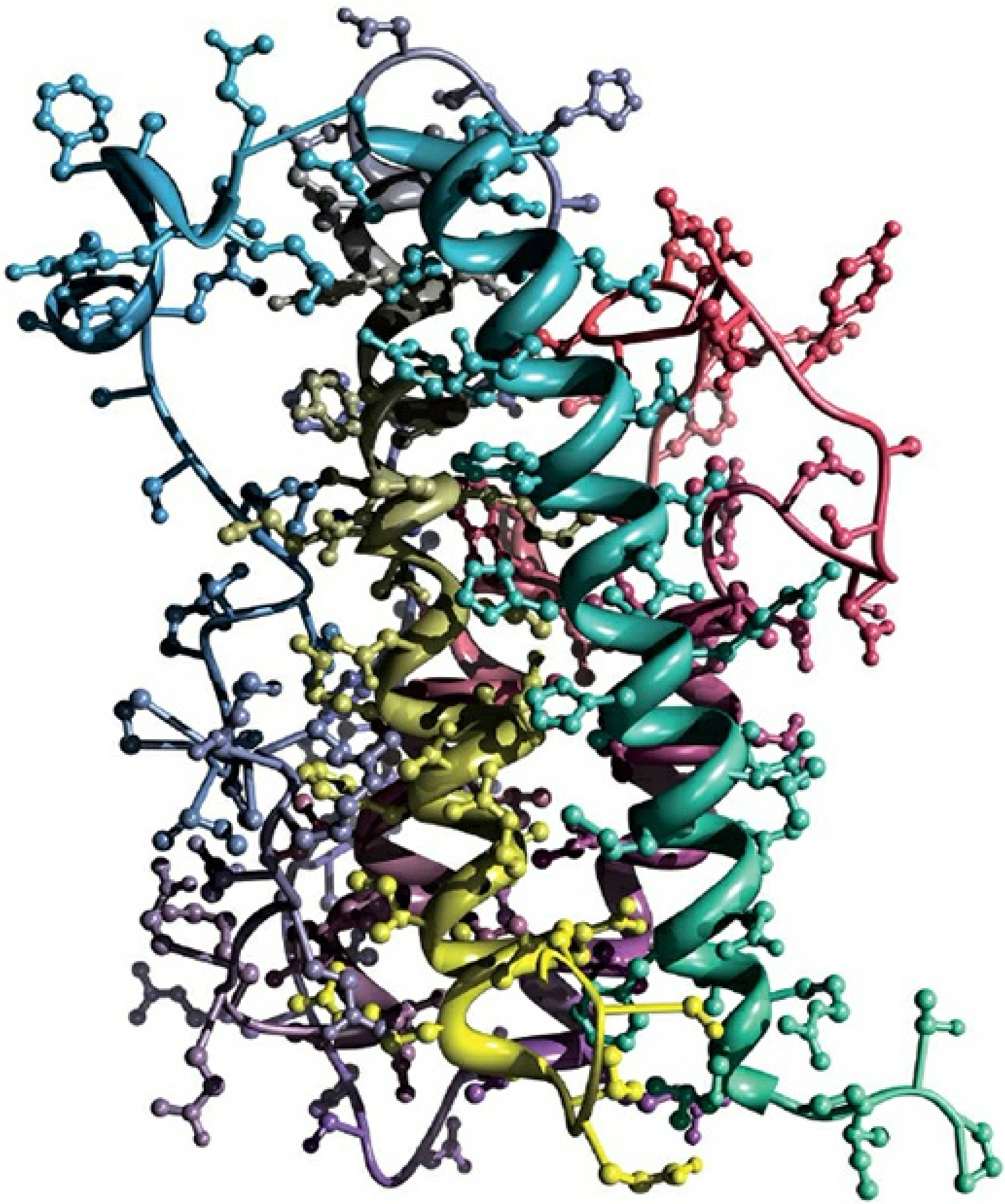
Fourier series are useful in countless applications today, ranging from vibration analysis to image processing—virtually any field in which a frequency analysis is important. For example, Fourier series help scientists characterize and better understand the chemical composition of stars or how the vocal tract produces speech.

Before French mathematician Joseph Fourier discovered his famous series, he accompanied Napoleon on his 1789 expedition of Egypt, where Fourier spent several years studying Egyptian artifacts. Fourier's research on the mathematical theory of heat began around 1804 when he was back in France, and in 1807 he had completed his important memoir *On the Propagation of Heat in Solid Bodies*. One of his interests was heat diffusion in different shapes. For these problems, researchers are usually given the temperatures at points on the surface, as well as at its edges, at time $t = 0$. Fourier introduced a series with sine and cosine terms in order to find solutions to these kinds of problems. More generally, he found that any differentiable function can be represented to arbitrary accuracy by a sum of sine and cosine functions, no matter how bizarre the function may look when graphed.

Biographers Jerome Ravetz and I. Grattan-Guinness note, "Fourier's achievement can be understood by [considering] the powerful mathematical tools he invented for the solutions of the equations, which yielded a long series of descendants and raised problems in mathematical analysis that motivated much of the leading work in that field for the rest of the century and beyond." British physicist Sir James Jeans (1877–1946) remarked, "Fourier's theorem tells us that every curve, no matter what its nature may be, or in what way it was originally obtained, can be exactly reproduced by superposing a sufficient number of simple harmonic curves—in brief, every curve can be built up by piling up waves."

SEE ALSO Development of Modern Calculus (1665), Wave Nature of Light (1801), Schrödinger's Wave Equation (1926).

Molecular model of human growth hormone. Fourier series and corresponding Fourier synthesis methods are used to determine molecular structures from X-ray diffraction data.



1808

Atomic Theory • *Clifford A. Pickover*

John Dalton (1766–1844)

John Dalton attained his professional success in spite of several hardships: He grew up in a family with little money; he was a poor speaker; he was severely color blind; and he was also considered to be a fairly crude or simple experimentalist. Perhaps some of these challenges would have presented an insurmountable barrier to any budding chemist of his time, but Dalton persevered and made exceptional contributions to the development of atomic theory, which states that all matter is composed of atoms of differing weights that combine in simple ratios in atomic compounds. During Dalton's time, atomic theory also suggested that these atoms were indestructible and that, for a particular element, all atoms were alike and had the same atomic weight.

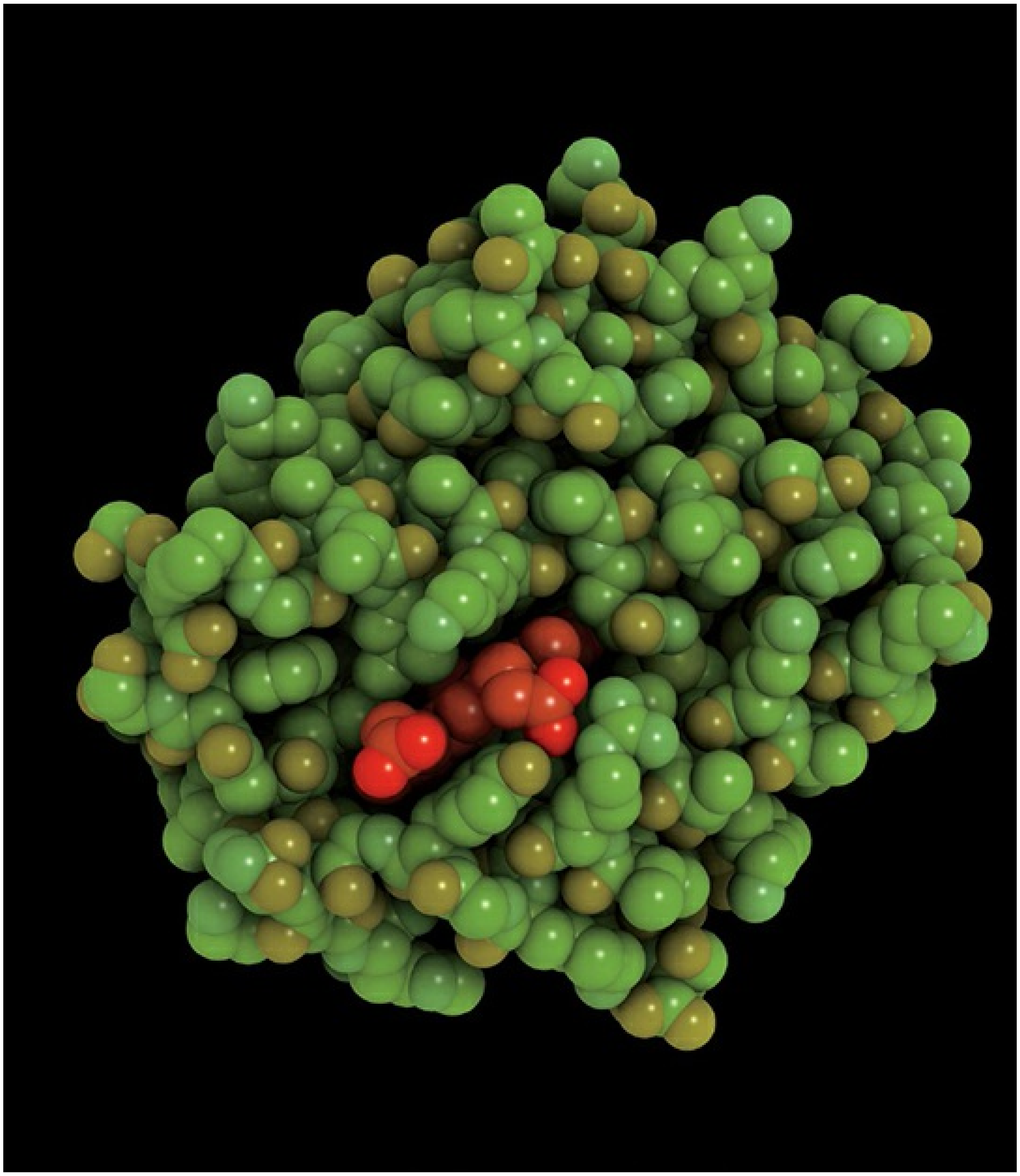
He also formulated the *Law of Multiple Proportions,* which stated that whenever two elements can combine to form different compounds, the masses of one element that combine with a fixed mass of the other are in a ratio of small integers, such as 1:2. These simple ratios provided evidence that atoms were the building blocks of compounds.

Dalton encountered resistance to atomic theory. For example, the British chemist Sir Henry Enfield Roscoe (1833–1915) mocked Dalton in 1887, saying, “Atoms are round bits of wood invented by Mr. Dalton.” Perhaps Roscoe was referring to the wood models that some scientists used in order to represent atoms of different sizes. Nonetheless, by 1850, the atomic theory of matter was accepted among a significant number of chemists, and most opposition disappeared.

The idea that matter was composed of tiny, indivisible particles was considered by the philosopher Democritus in Greece in the fifth century BCE, but this was not generally accepted until after Dalton’s 1808 publication of *A New System of Chemical Philosophy*. Today, we understand that atoms are divisible into smaller particles, such as protons, neutrons, and electrons. Quarks are even smaller particles that combine to form other subatomic particles such as protons and neutrons.

SEE ALSO Kinetic Theory (1859), Electron (1897), Atomic Nucleus (1911), Quarks (1964).

LEFT: *Engraving of John Dalton, by William Henry Worthington (c. 1795–c. 1839).* RIGHT: *According to atomic theory, all matter is composed of atoms. Pictured here is a hemoglobin molecule with atoms represented as spheres. This protein is found in the red blood cell.*



1812

Laplace's *Théorie Analytique des Probabilités* • *Clifford A. Pickover*

Pierre-Simon, **Marquis de Laplace** (1749–1827)

The first major treatise on probability that combines probability theory and calculus was French mathematician and astronomer Pierre-Simon Laplace's *Théorie Analytique des Probabilités* (*Analytical Theory of Probabilities*). Probability theorists focus on random phenomena. Although a single roll of the dice may be considered a random event, after numerous repetitions, certain statistical patterns become apparent, and these patterns can be studied and used to make predictions.

The first edition of Laplace's *Théorie Analytique* was dedicated to Napoleon Bonaparte and discusses methods of finding probabilities of compound events from component probabilities. The book also discusses the method of least squares and Buffon's Needle and considers many practical applications.

Stephen Hawking calls *Théorie Analytique* a "masterpiece" and writes, "Laplace held that because the world is determined, there can be no probabilities in things. Probability results in our lack of knowledge." According to Laplace, nothing would be "uncertain" for a sufficiently advanced being—a conceptual model that remained strong until the rise of quantum mechanics and chaos theory in the twentieth century.

To explain how probabilistic processes can yield predictable results, Laplace asks readers to imagine several urns arranged in a circle. One urn contains only black balls, while another contains only white balls. The other urns have various ball mixtures. If we withdraw a ball, place it in the adjacent urn, and continue around the circle, eventually the ratio of black to white balls will be approximately the same in all of the urns. Here, Laplace shows how random "natural forces" can create results that have a predictability and order. Laplace writes, "It is remarkable that this science, which originated in the consideration of games of chance, should become the most important object of human knowledge. . . . The most important questions in life are, for the most part, really only problems of probability." Other famous probabilists include Gerolamo Cardano (1501–1576), Pierre de Fermat (1601–1665), Blaise Pascal (1623–1662), and Andrey Nikolaevich Kolmogorov (1903–1987).

SEE ALSO Development of Modern Calculus (1665), Law of Large Numbers (1713), Normal Distribution Curve (1733).

Laplace felt it was remarkable that probability, which originated in analysis of games of chance, should become "the most important object of human knowledge . . ."


32
0
26
35
12
28

1822

Babbage Mechanical Computer • *Clifford A. Pickover*

Charles Babbage (1792–1871), **Augusta Ada King**, **Countess of Lovelace** (1815–1852)

Charles Babbage was an English analyst, statistician, and inventor who was also interested in the topic of religious miracles. He once wrote, “Miracles are not a breach of established laws, but . . . indicate the existence of far higher laws.” Babbage argued that miracles could occur in a mechanistic world. Just as Babbage could imagine programming strange behaviors on his calculating machines, God could program similar irregularities in nature. While investigating biblical miracles, he suggested that the chance of a man rising from the dead is one in 10^{12}.

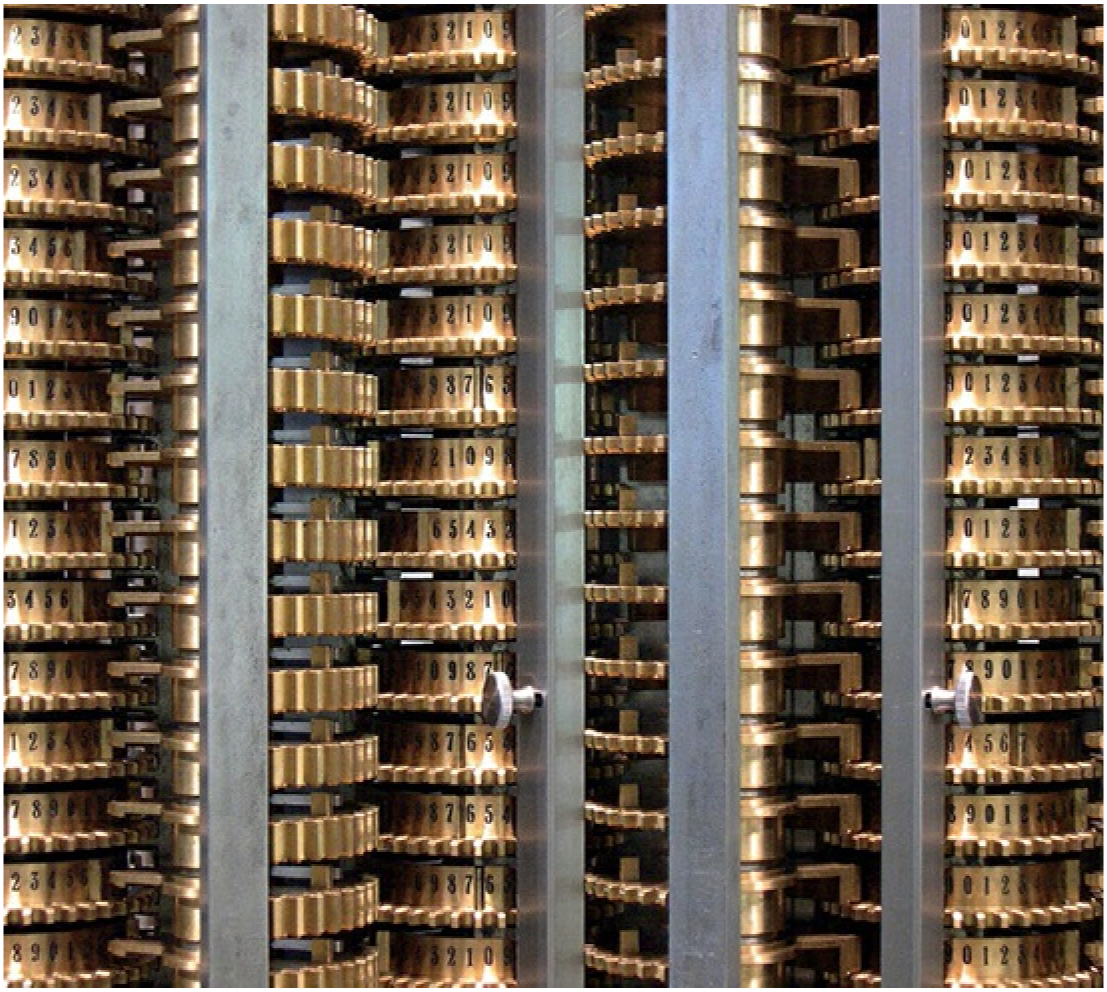
Babbage is often considered the most important mathematician-engineer involved in the prehistory of computers. In particular, he is famous for conceiving an enormous hand-cranked mechanical calculator, an early progenitor of our modern computers. Babbage thought the device would be most useful in producing mathematical tables, but he worried about mistakes that would be made by humans who transcribed the results from its 31 metal output wheels. Today, we realize that Babbage was around a century ahead of his time and that the politics and technology of his era were inadequate for his lofty dreams.

Babbage’s Difference Engine, begun in 1822 but never completed, was designed to compute values of polynomial functions, using about 25,000 mechanical parts. He also had plans to create a more general-purpose computer, the Analytical Engine, which could be programmed using punch cards and had separate areas for number storage and computation. Estimates suggest that an Analytical Engine capable of storing 1,000 50-digit numbers would be more than 100 feet (about 30 meters) in length. Ada Lovelace, the daughter of the English poet Lord Byron, gave specifications for a program for the Analytical Engine. Although Babbage provided assistance to Ada, many consider Ada to be the first computer programmer.

In 1990, novelists William Gibson and Bruce Sterling wrote *The Difference Engine*, which asked readers to imagine the consequences of Babbage's mechanical computers becoming available to Victorian society.

SEE ALSO Slide Rule (1621), ENIAC (1946), ARPANET (1969)

Working model of a portion of Charles Babbage's Difference Engine, currently located at the London Science Museum.



1824

Carnot Engine • *Clifford A. Pickover*

Nicolas Léonard Sadi Carnot (1796–1832)

Much of the initial work in thermodynamics—the study of the conversion of energy between work and heat—focused on the operation of engines and how fuel, such as coal, could be efficiently converted to useful work by an engine. Sadi Carnot is probably most often considered the "father" of thermodynamics, thanks to his 1824 work *Réflexions sur la puissance motrice du feu* (*Reflections on the Motive Power of Fire*).

Carnot worked tirelessly to understand heat flow in machines partly because he was disturbed that British steam engines seemed to be more efficient than French engines. During his day, steam engines usually burned wood or coal in order to convert water into steam. The high-pressure steam moved the pistons of the engine. When the steam was released through an exhaust port, the pistons returned to their original positions. A cool radiator converted the exhaust steam to water, so it could be heated again to steam in order to drive the pistons.

Carnot imagined an ideal engine, known today as the *Carnot engine*, that would theoretically have a work output equal to that of its heat input and not lose even a small amount of energy during the conversion. After experiments, Carnot realized that no device could perform in this ideal matter—some energy had to be lost to the environment. Energy in the form of heat could not be converted completely into mechanical energy. However, Carnot did help engine designers improve their engines so that the engines could work close to their peak efficiencies.

Carnot was interested in "cyclical devices" in which, at various parts of their cycles, the device absorbs or rejects heat; it is impossible to make such an engine that is 100 percent efficient. This impossibility is yet another way of stating the Second Law of Thermodynamics. Sadly, in 1832 Carnot contracted cholera and, by order of the health office, nearly all his books, papers, and other personal belongings had to be burned!

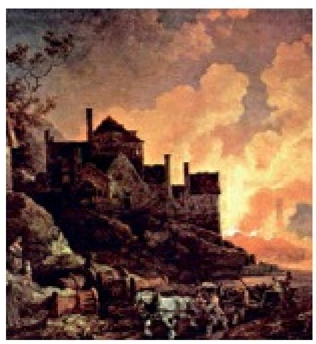
SEE ALSO Second Law of Thermodynamics (1850), Steam Turbine (1890), Internal Combustion Engine (1908).

LEFT: *An 1813 portrait of Sadi Carnot.* RIGHT: *Locomotive steam engine. Carnot worked to understand heat flow in machines, and his theories have relevance to this day. During his time, steam engines usually burned wood or coal.*

1824

Greenhouse Effect • *Clifford A. Pickover*

Joseph Fourier (1768–1830), **Svante August Arrhenius** (1859–1927), **John Tyndall** (1820–1893)



“Despite all its bad press,” write authors Joseph Gonzalez and Thomas Sherer, “the process known as the *greenhouse effect* is a very natural and necessary phenomenon. . . . The atmosphere contains gases that enable sunlight to pass through to the earth’s surface but hinder the escape of reradiated heat energy. Without this natural greenhouse effect, the earth would be much too cold to sustain life.” Or, as Carl Sagan once wrote, “A little greenhouse effect is a good thing.”

Generally speaking, the greenhouse effect is the heating of the surface of a planet as a result of atmospheric gases that absorb and emit infrared radiation, or heat energy. Some of the energy reradiated by the gases escapes into outer space; another portion is reradiated back toward the planet. Around 1824, mathematician Joseph Fourier wondered how the Earth stays sufficiently warm to support life. He proposed that although some heat does escape into space, the atmosphere acts a little like a translucent dome—a glass lid of a pot, perhaps—that absorbs some of the heat of the Sun and reradiates it downward to the Earth.

In 1863, British physicist and mountaineer John Tyndall reported on experiments that demonstrated that water vapor and carbon dioxide absorbed substantial amounts of heat. He concluded that water vapor and carbon dioxide must therefore play an important role in regulating the temperature at the Earth's surface. In 1896, Swedish chemist Svante Arrhenius showed that carbon dioxide acts as a very strong "heat trap" and that halving the amount in the atmosphere might trigger an ice age. Today we use the term *anthropogenic global warming* to denote an enhanced greenhouse effect due to human contributions to greenhouse gases, such as the burning of fossil fuels.

Aside from water vapor and carbon dioxide, methane from cattle belching can also contribute to the greenhouse effect. "Cattle belching?" Thomas Friedman writes. "That's right—the striking thing about greenhouse gases is the diversity of sources that emit them. A herd of cattle belching can be worse than a highway full of Hummers."

SEE ALSO Conservation of Energy (1843), Internal Combustion Engine (1908), Photosynthesis (1947).

LEFT: *"Coalbrookdale by Night" (1801), by Philip James de Loutherbourg (1740–1812), showing the Madeley Wood Furnaces, a common symbol of the early Industrial Revolution.* RIGHT: *Large changes in manufacturing, mining, and other activities since the Industrial Revolution have increased the amount of greenhouse gases in the air. For example, steam engines, fuelled primarily by coal, helped to drive the Industrial Revolution.*

1825

Ampère's Law of Electromagnetism •

Clifford A. Pickover

André-Marie Ampère (1775–1836), **Hans Christian Ørsted** (1777–1851)

By 1825, French physicist André-Marie Ampère had established the foundation of electromagnetic theory. The connection between electricity and magnetism was largely unknown until 1820, when Danish physicist Hans Christian Ørsted discovered that a compass needle moves when an electric current is switched on or off in a nearby wire. Although not fully understood at the time, this simple demonstration suggested that electricity and magnetism were related phenomena, a finding that led to various applications of electromagnetism and eventually culminated in telegraphs, radios, TVs, and computers.

Subsequent experiments during a period from 1820 to 1825 by Ampère and others showed that any conductor that carries an electric current *I* produces a magnetic field around it. This basic finding, and its various consequences for conducting wires, is sometimes referred to as *Ampère's*

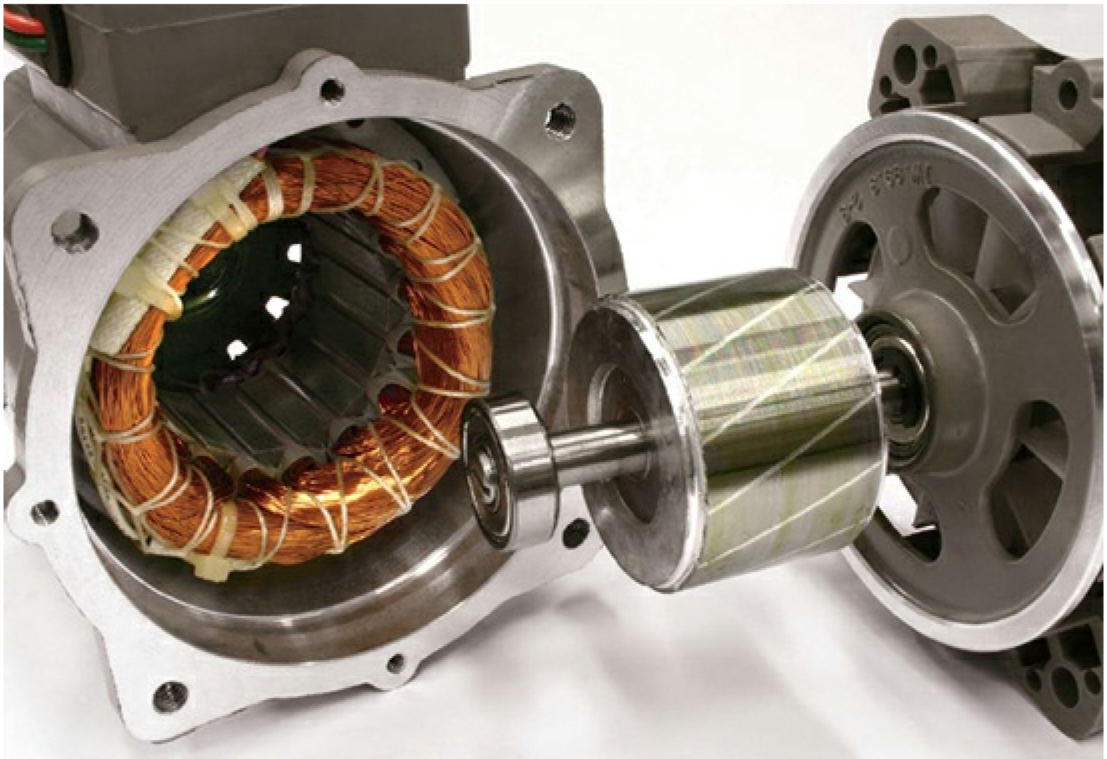
Law of Electromagnetism. For example, a current-carrying wire produces a magnetic field B that circles the wire. (The use of bold signifies a vector quantity.) B has a magnitude that is proportional to I, and points along the circumference of an imaginary circle of radius r centered on the axis of the long, straight wire. Ampère and others showed that electric currents attract small bits of iron, and Ampère proposed a theory that electric currents are the source of magnetism.

Readers who have experimented with electromagnets, which can be created by wrapping an insulated wire around a nail and connecting the ends of the wire to a battery, have experienced Ampère's Law first hand. In short, Ampère's Law expresses the relationship between the magnetic field and the electric current that produces it.

Additional connections between magnetism and electricity were demonstrated by the experiments of American scientist Joseph Henry (1797–1878), British scientist Michael Faraday (1791–1867), and James Clerk Maxwell. French physicists Jean-Baptiste Biot (1774–1862) and Félix Savart (1791–1841) also studied the relationship between electrical current in wires and magnetism. A religious man, Ampère believed that he had proven the existence of the soul and of God.

SEE ALSO Coulomb's Law of Electrostatics (1785), Faraday's Laws of Induction (1831), Maxwell's Equations (1861).

LEFT: *Engraving of André-Marie Ampère by A. Tardieu (1788–1841).* RIGHT: *Electric motor with exposed rotor and coil. Electromagnets are widely used in motors, generators, loudspeakers, particle accelerators, and industrial lifting magnets.*



1827

Brownian Motion • *Clifford A. Pickover*

Robert Brown (1773–1858), **Jean-Baptiste Perrin** (1870–1942), **Albert Einstein** (1879–1955)

In 1827, Scottish botanist Robert Brown was using a microscope to study pollen grains suspended in water. Particles within the vacuoles of the pollen grains seemed to dance about in a random fashion. In 1905, Albert Einstein predicted the movement of such kinds of small particles by suggesting that they were constantly being buffeted by water molecules. At any instant in time, just by chance, more molecules would strike one side of the particle than another side, thereby causing the particle to momentarily move slightly in a particular direction. Using statistical rules, Einstein demonstrated that this Brownian motion could be explained by random fluctuations in such collisions. Moreover, from this motion, one could determine the dimensions of the hypothetical molecules that were bombarding the macroscopic particles.

In 1908, French physicist Jean-Baptiste Perrin confirmed Einstein's explanation of Brownian motion. As a result of Einstein and Perrin's work, physicists were finally compelled to accept the reality of atoms and molecules, a subject still ripe for debate even at the beginning of the twentieth century. In concluding his 1909 treatise on this subject, Perrin wrote, "I think that it will henceforth be difficult to defend by rational arguments a hostile attitude to molecular hypotheses."

Brownian motion gives rise to diffusion of particles in various media and is so general a concept that it has wide applications in many fields, ranging from the dispersal of pollutants to the understanding of the relative sweetness of syrups on the surface of the tongue. Diffusion concepts help us understand the effect of pheromones on ants or the spread of muskrats in Europe following their accidental release in 1905. Diffusion laws have been used to model the concentration of smokestack contaminants and to simulate the displacement of hunter-gatherers by farmers in Neolithic times. Researchers have also used diffusion laws to study diffusion of radon in the open air and in soils contaminated with petroleum hydrocarbons.

SEE ALSO Atomic Theory (1808), Kinetic Theory (1859), Boltzmann's Entropy Equation (1875).

Scientists used Brownian motion and diffusion concepts to model muskrat propagation. In 1905, five muskrats were introduced to Prague from the U.S. By 1914, their descendants had spread 90 miles in all directions. In 1927, they numbered over 100 million.

1828

Germ-Layer Theory of Development •

Michael C. Gerald with Gloria E. Gerald

Karl Ernst von Baer (1792–1876), **Christian Heinrich Pander** (1794–1865), **Robert Remak** (1815–1865), **Hans Spemann** (1869–1941)

Casper Friedrich Wolff provided evidence supporting the epigenetic theory of generation—namely that, after conception, each individual begins as an undifferentiated mass in the egg and gradually differentiates and grows. Wolff's theory (1759) was largely disregarded by the scientific community; however, during the following century, it was revisited and served as the foundation for the germ-layer theory.

In 1815, the Estonian-born Karl Ernst von Baer attended the University of Würzburg, where he was introduced to the new field of embryology. His anatomy professor encouraged him to pursue research on chick embryo development but, unable to pay for the eggs or hiring an attendant to watch the incubators, he turned the project over to his more-affluent friend Christian Heinrich Pander, who identified three distinct regions in the chick embryo.

Von Baer extended Pander's findings in 1828 to show that in all vertebrate embryos, there are three concentric germ layers. In 1842, the Polish-German embryologist Robert Remak provided microscopic evidence for the existence of these layers and designated them by names still in use. The ectoderm or outermost layer develops into the skin and nerves; from the endoderm, the innermost layer, comes the digestive system and lungs; and between these layers, the mesoderm, is derived blood, heart, kidneys, gonads, bones, and connective tissues. It was subsequently determined that while all vertebrates exhibit bilateral symmetry and have three germ layers, animals that display radial symmetry (hydra and sea anemone) have two layers, while only the sponge has a single germ layer.

Von Baer proposed other principles in embryology: General features of a large group of animals appear earlier than the specialized features seen in a smaller group. All vertebrates begin development with skin that differentiates to scales in fish and reptiles, feathers in birds, and hair and fur in mammals. In 1924, Hans Spemann's discovery of embryonic induction explained how groups of cells form particular tissues and organs.

SEE ALSO Discovery of Sperm (1678), Cell Division (1855), Epigenetics (1983).

Eggs, such as this one-week-old chicken egg, are candled to observe the development of a chick or duck embryo and veins. Candling is performed in a darkened room with the egg perched on a light.

1829

Blood Transfusion • *Clifford A. Pickover*

James Blundell (1791–1878), **Karl Landsteiner** (1868–1943)

"The history of blood transfusion is a fascinating story and is marked by alternating periods of intense enthusiasm and periods of disillusionment, more so than the introduction of any other therapeutic measure," writes the surgeon Raymond Hurt. "Its full potential was not achieved until the discovery of blood groups and introduction of a satisfactory anticoagulant."

Blood transfusion often refers to the transfer of blood, or blood components, from one person to another in order to combat blood loss during trauma or surgery. Transfusions of blood may also be required during the treatment of various diseases such as hemophilia and sickle-cell anemia.

Various animal-to-animal blood transfusions, as well as animal-to-human transfusions, had been attempted in the 1600s in Europe. However, the English obstetrician James Blundell is credited with the first *successful* transfusion of blood from one human to another. Not only did he begin to place the art of transfusion on a scientific basis, he reawakened interest in a procedure that was generally quite unsafe. In 1818, Blundell had used several donors to transfuse a man dying from stomach cancer, but the man died about two days later. In 1829, through the use of a syringe, he transfused blood from a husband to his wife, who was bleeding heavily after giving birth. She happily survived, representing the first successful documented transfusion.

Blundell soon came to realize that many transfusions led to kidney damage and death. It was not until around 1900 that Austrian physician Karl Landsteiner discovered three blood groups—A, B, and O—and found that transfusion between people with the same blood group usually led to safe transfusions. A fourth blood type, AB, was discovered shortly thereafter. The development of electrical refrigeration led to the first "blood banks" in the mid-1930s. After the Rh blood factor was discovered in 1939, dangerous blood-transfusion reactions became rare.

Transfusions have sometimes been limited due to prejudice. For example, in the 1950s, Louisiana made it a crime for physicians to give a white person "black blood" without obtaining prior permission.

SEE ALSO Circulatory System (1628), Cell Division (1855), Heart Transplant (1967).

Hand-colored engraved image, The Transfusion of Blood—An Operation at the Hôpital de la Pitié (1874), by Miranda, from Harper's Weekly.

1829

Non-Euclidean Geometry • *Clifford A. Pickover*

Nicolai Ivanovich Lobachevsky (1792–1856), **János Bolyai** (1802–1860), **Georg Friedrich Bernhard Riemann** (1826–1866)

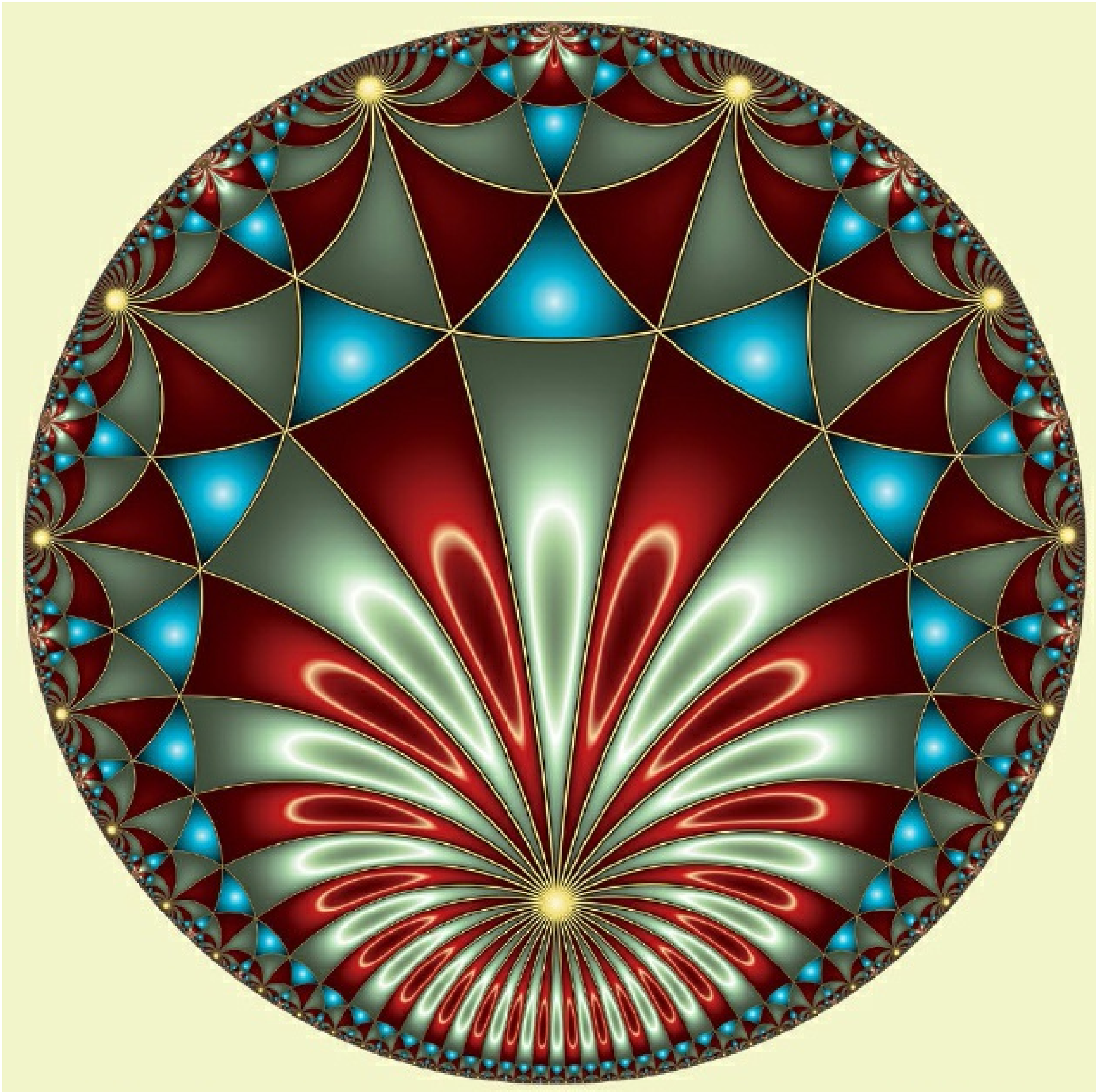
Since the time of Euclid (c. 325–270 BCE), the so-called parallel postulate seemed to reasonably describe how our three-dimensional world works. According to this postulate, given a straight line and a point not on that line, in their plane only one straight line through the point exists that never intersects the original line.

Over time, the formulations of non-Euclidean geometry, in which this postulate does not hold, have had dramatic consequences. Einstein said about non-Euclidean geometry: “To this interpretation of geometry, I attach great importance, for should I have not been acquainted with it, I never would have been able to develop the theory of relativity.” In fact, Einstein’s General Theory of Relativity represents space-time as a non-Euclidean geometry in which space-time actually warps, or curves, near gravitating bodies such as the sun and planets. This can be visualized by imagining a bowling ball sinking into a rubber sheet. If you were to place a marble into the depression formed by the stretched rubber sheet, and give the marble a sideways push, it would orbit the bowling ball for a while, like a planet orbiting the sun.

In 1829, Russian mathematician Nicolai Lobachevsky published *On the Principles of Geometry*, in which he imagined a perfectly consistent geometry that results from assuming that the parallel postulate is false. Several years earlier, Hungarian mathematician János Bolyai had worked on a similar non-Euclidean geometry, but his publication was delayed until 1832. In 1854, German mathematician Bernhard Riemann generalized the findings of Bolyai and Lobachevsky by showing that various non-Euclidean geometries are possible, given the appropriative number of dimensions. Riemann once remarked, “The value of non-Euclidean geometry lies in its ability to liberate us from preconceived ideas in preparation for the time when exploration of physical laws might demand some geometry other than the Euclidean.” His prediction was realized later with Einstein’s General Theory of Relativity.

SEE ALSO Euclid’s *Elements* (c. 300 BCE), Descartes’ *La Géométrie* (1637), Projective Geometry (1639), Riemann Hypothesis (1859).

One form of non-Euclidean geometry is exemplified by Jos Leys’s hyperbolic tiling. Artist M. C. Escher also experimented with non-Euclidean geometries in which the entire universe could be compressed and represented in a finite disk.



1831

Cell Nucleus • *Michael C. Gerald with Gloria E. Gerald*

Antonie van Leeuwenhoek (1632–1723), **Franz Bauer** (1758–1840), **Robert Brown** (1773–1858), **Matthias Schleiden** (1804–1881), **Oscar Hertwig** (1849–1922), **Albert Einstein** (1879–1955)

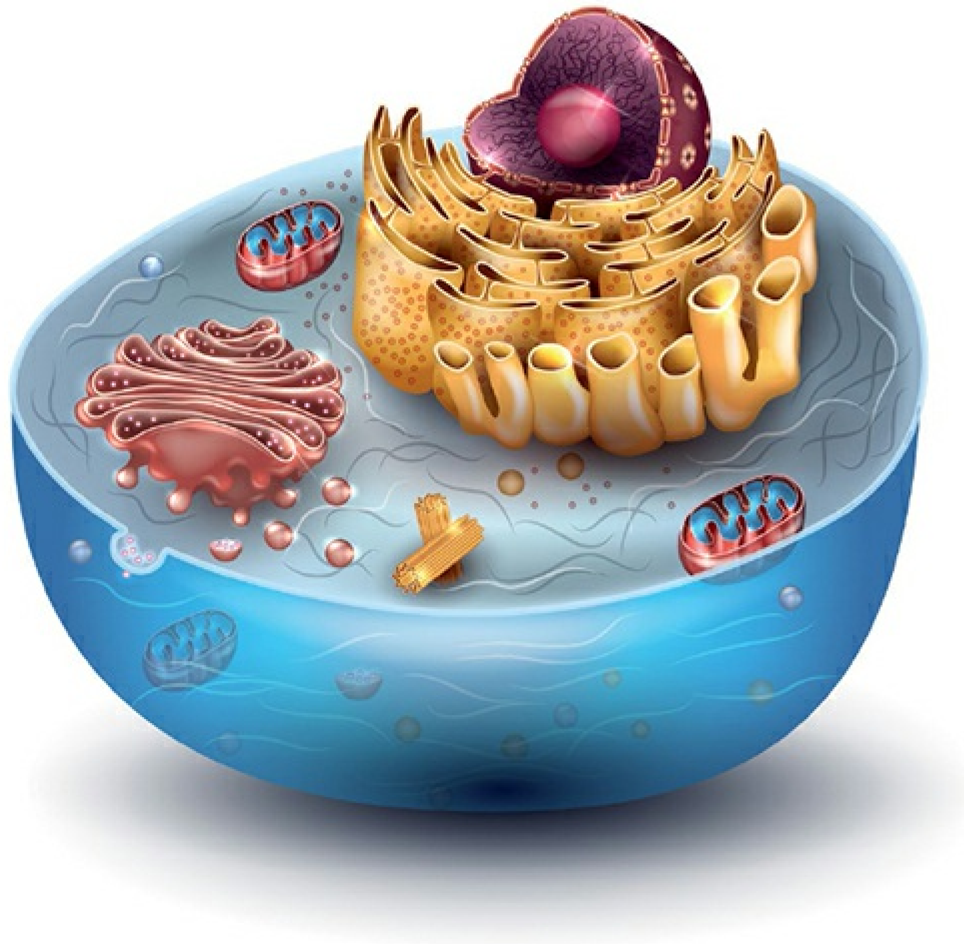
During the 1670s, the Dutch microscopist Antonie van Leeuwenhoek was the first to see a world previously unknown, which included the fibers of a muscle, bacteria, sperm cells, and the nucleus in the red blood cell of salmon. The next reported sighting of a cell nucleus was in 1802 by Franz Bauer, an Austrian microscopist and botanical artist. However, credit for its discovery is generally assigned to the Scottish botanist Robert Brown. When studying the epidermis (outer layer) of an orchid, he saw an opaque spot that was also present during an early stage of pollen formation; he called this spot a *nucleus*. Brown first described its appearance to his colleagues at a meeting of the Linnean Society of London in 1831 and published his findings two years later. Both Brown and Bauer thought that the nucleus was a cell structure that was unique to monocots, a plant group that includes orchids. In 1838, the German botanist Matthias Schleiden, the co-discoverer of the cell theory, first recognized the connection between the nucleus and cell division, and in 1877, Oscar Hertwig demonstrated its role in fertilization of the egg.

CARRIER OF GENETIC MATERIAL. The nucleus, the largest organelle within the cell, contains chromosomes and deoxyribonucleic acid (DNA), and regulates cell metabolism, cell division, gene expression, and protein synthesis. The nuclear envelope—a double membrane surrounding the nucleus and separating it from the rest of the cell—is in continuity with the rough endoplasmic reticulum, the site of protein synthesis.

At the time of his 1831 discovery, Brown was an established botanist. Earlier in his career, from 1801–1805, he collected 3,400 species of plants while in Australia and described and published reports of 1,200 of these. In 1827, he reported on microscopic pollen grains (and later other particles) moving continuously and randomly through a liquid or gas medium colliding with one another. An explanation of this Brownian motion came in 1905, when Albert Einstein explained that it resulted from molecules of water that were not visible hitting visible pollen grain molecules.

SEE ALSO *Micrographia* (1665), Discovery of Sperm (1678), Cell Division (1855), Chromosomal Theory of Inheritance (1902), Ribosomes (1955).

Artistic depiction of the interior of an animal cell, featuring its various organelles. The nucleus is represented in purple at the back of the image, and it contains the nucleolus (depicted as a smaller internal sphere) and chromatin fibers (DNA, protein, and RNA).



1831

Darwin and the Voyages of the *Beagle*

• Michael C. Gerald with Gloria E. Gerald

Charles Darwin (1809–1882)

There is little to suggest that prior to 1859, Charles Darwin would rank among the most important biologists, and that his *Origin of Species* (1859) perhaps would be the most significant book written on science. His father was a financially and socially successful physician, and his mother was the daughter of Josiah Wedgwood, founder of the pottery company bearing his family name. Charles's grandfather was Erasmus Darwin, a distinguished eighteenth-century intellectual. Neither his year of medical studies nor his bachelor's studies at Cambridge were marked with distinction. His time was spent exploring nature and hunting.

Captain Robert FitzRoy was looking for a "gentleman passenger" who could serve as a recorder and collector of biological samples on a five-year voyage of the *HMS Beagle* that was intended to circumnavigate the globe, with emphasis on charting the South American coastline. The twenty-two-year-old Darwin was selected for this unpaid position because of his keen interest in the natural sciences but, as important, he could serve as a socially equal companion to the captain who was but four years his senior. When Darwin set sail in 1831, he shared the belief of most Europeans in the divine creation of the world and the unchanging nature of its inhabitants.

When not seasick, Darwin was diligently observing and collecting animals, marine invertebrates, insects, and fossils of extinct animals. He also experienced an earthquake in Chile. The most memorable segment of his voyage was the five weeks he spent on the Galápagos Islands, ten volcanic islands some 600 miles (1,000 kilometers) west of Ecuador. Among his many collectables were four mockingbirds caught on four islands; he noted that each was different. He also brought back to England fourteen finches whose beaks differed in size and shape. When Darwin returned to England in 1835, he was a well-recognized naturalist, a reputation enhanced by his presentations, papers, and a popular work entitled *Journal of Researches* (renamed *The Voyage of the Beagle*).

SEE ALSO Linnaean Classification of Species (1735), Fossil Record and Evolution (1836), Darwin's Theory of Natural Section (1859).

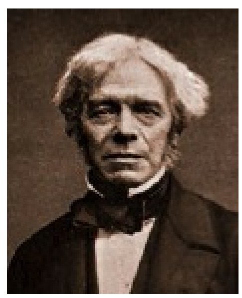
Topographical and bathymetric map of the Galápagos Islands, located west of Ecuador, where Darwin found fourteen finches whose beaks were different in size and shape—an observation that proved to be a major building block in his theory of natural selection (1859).


PACIFIC OCEAN
Galápagos Islands
Darwin
Wolf
Pinta
Marchena
Genovesa
San Salvador
Fernandina
Isabela
Santa Cruz
Santa Fé
San Cristóbal
Floreana
Española
Puerto Villamil
Puerto Baquerizo Moreno
Island
Alternate Name
Peak
Provincial Capital
Cantonal Capital
Village
Airport
PACIFIC
OCEAN
COLOMBIA
ECUADOR
PERU
PANAMA

1831

Faraday’s Laws of Induction • *Clifford A. Pickover*

Michael Faraday (1791–1867)



“Michael Faraday was born in the year that Mozart died,” Professor David Goodling writes. “Faraday’s achievement is a lot less accessible than Mozart’s [but . . .] Faraday’s contributions to modern life and culture are just as great. . . . His discoveries of . . . magnetic induction laid the foundations for modern electrical technology . . . and made a framework for unified field theories of electricity, magnetism, and light.”

English scientist Michael Faraday’s greatest discovery was that of electromagnetic induction. In 1831, he noticed that when he moved a magnet through a stationary coil of wire, he always produced an electric current in the wire. The induced electromotive force was equal to the rate of change of the magnetic flux. American scientist Joseph Henry (1797–1878) carried out similar experiments. Today, this induction phenomenon plays a crucial role in electric power plants.

Faraday also found that if he moved a wire loop near a stationary permanent magnet, a current flowed in the wire whenever it moved. When Faraday experimented with an electromagnet and caused the magnetic field surrounding the electromagnet to change, he then detected electric current flow in a nearby but separate wire.

Scottish physicist James Clerk Maxwell (1831–1879) later suggested that changing the magnetic flux produced an electric field that not only caused electrons to flow in a nearby wire, but that the field also existed in space—even in the absence of electric charges. Maxwell expressed the change in magnetic flux and its relation to the induced electromotive force (ε or emf) in what we call Faraday's Law of Induction. The magnitude of the emf induced in a circuit is proportional to the rate of change of the magnetic flux impinging on the circuit.

Faraday believed that God sustained the universe and that he was doing God's will to reveal truth through careful experiments and through his colleagues, who tested and built upon his results. He accepted every word of the Bible as literal truth, but meticulous experiments were essential in this world before any other kind of assertion could be accepted.

SEE ALSO Ampère's Law of Electromagnetism (1825), Maxwell's Equations (1861), Power Grid (1878).

LEFT: *Photograph of Michael Faraday (c. 1861) by John Watkins (1823–1874).* RIGHT: *A dynamo, or electrical generator, from G. W. de Tunzelmann's Electricity in Modern Life, 1889. Power stations usually rely on a generator with rotating elements that convert mechanical energy into electrical energy through relative motions between a magnetic field and an electrical conductor.*

1836

Fossil Record and Evolution • *Michael C. Gerald with Gloria E. Gerald*

Georges Cuvier (1769–1832), **Richard Owen** (1804–1892), **Charles Darwin** (1809–1882)

Prior to the nineteenth century, uncovered fossilized skeletal remains appeared to differ rather abruptly and dramatically in form and without apparent intermediate transitions. This was widely interpreted as support of creationism and the view that no animal species had ever become extinct. When Cuvier studied fossilized mammalian skeletons in 1796, he rejected the concept of evolution. By contrast, analogous fossilized skeletons were one of the major linchpins Darwin used when formulating his theory of evolution.

Georges Cuvier, the great French naturalist-zoologist, combined his knowledge of paleontology with his expertise in comparative anatomy when comparing the fossilized remains of mammals with their living counterparts. In 1796, Cuvier presented two papers; one comparing living elephants with extinct mammoths and, in the other, the giant sloth and the extinct Megatherium found in Paraguay. His findings and many of the geological features of the earth, he believed, could best be explained by several catastrophic events, causing the extinction of many animal species and followed by successive creations. He was a major proponent of catastrophism and highly critical of evolution.

Charles Darwin's voyage on the *Beagle* in the early 1830s took him to Patagonia, where he found the fossilized remains of mastodons, Megatheria, horses, and the large armadillo-like Glyptodons. Upon returning to England in 1836, Darwin took the fossils and his detailed notes to anatomist Richard

Owen. Owen determined that these remains were more closely related to living mammals in South America than anywhere else. (He later rejected Darwin's theory of natural selection.) In his *Origin of Species* (1859), Darwin noted the importance of these fossils and acknowledged that while "missing links" or transitional forms between the fossilized and living forms might never be found, and represented the greatest objection to his conclusions, nevertheless, the evidence strongly supported his theory of evolution. In 2012, a collection of 314 fossil slides collected by Darwin and his peers were rediscovered in a corner of the British Geological Survey, after being lost for more than 150 years.

SEE ALSO Linnaean Classification of Species (1735), Darwin's Theory of Natural Section (1859), Radiocarbon Dating (1949).

The first discoveries of fossil remains of extinct mammals in the 1790s challenged support for the concept that living organisms were unchanged since the time of creation. This image is of an ammonite, an extinct marine invertebrate classified as a mollusk, whose name was inspired by tightly coiled rams' horns.

1837

Nitrogen Cycle and Plant Chemistry •

Michael C. Gerald with Gloria E. Gerald

Jean-Baptiste Boussingault (1802–1887), **Hermann Hellriegel** (1831–1895), **Martinus Beijerinck** (1851–1931)

Discovered in 1772, nitrogen constitutes some 78 percent of the earth's atmosphere—four times that of oxygen—and is an essential component of amino acids, proteins, and nucleic acids. Through a series of mutually beneficial interrelationships, nitrogen in decomposing plant and animal material is made available as a soluble plant nutrient and then converted to a gaseous form and returned to the atmosphere.

That nitrogen must be reduced (fixed before use) by plants or animals was determined by the French agricultural chemist Jean-Baptiste Boussingault. From 1834 to 1876, at his farm in Alsace, France, he established the world's first agricultural research station, applying chemical experimental methods to the fields. Boussingault also determined the nature of nitrogen's movement between plants, animals, and the physical environment, and studied such related problems as soil fertilization, crop rotation, plant and soil fixation of nitrogen, ammonia in rainwater, and nitrification.

In 1837, Boussingault disproved the general belief that plants absorbed nitrogen directly from the atmosphere and showed that they did so from the soil as nitrates. The following year, he discovered that nitrogen was essential for both plants and animals, and that both herbivores and carnivores obtain their nitrogen from plants. His chemical findings laid the foundation for our current understanding of the nitrogen cycle.

In 1888, the German agricultural chemist Hermann Hellriegel and the Dutch botanist and microbiologist Martinus Beijerinck independently discovered the mechanism by which leguminous plants utilize atmospheric nitrogen (N_2) and soil microbes convert it to ammonia (NH_3), nitrates (NO_3), and nitrites (NO_2). Symbiotic (mutualistic) nitrogen-fixing bacteria, such as *Rhizobium*, acting in plants of the legume family—including soybeans, alfalfa, kudzu, peas, beans, and peanuts—enter the root hairs of the root system of the plant, multiply, and stimulate the formation of root nodules. Within the nodules, the bacteria convert nitrogen to nitrates, which are utilized for growth by the legumes. When the plant dies, the fixed nitrogen is released, making it available for use by other plants, and thereby fertilizing the soil.

SEE ALSO Agriculture (c. 10,000 BCE) Ecological Interactions (1859), Photosynthesis (1947).

This World War II poster promotes the harvesting of legumes, which provide a food source and utilize atmospheric nitrogen to fertilize the soil.


HARVEST
LEGUME
& GRASS
SEED
FOR YOUR USE AND THE NATION'S NEED

1837

Telegraph System • *Marshall Brain*

Charles Wheatstone (1802–1875), **William Fothergill Cook** (1806–1879)

When we think of a telegraph system, we probably think of a person in an office tapping Morse code messages on a key, and receiving messages with a clicking metal bar. This arrangement, developed by English inventor William Fothergill Cook and scientist Charles Wheatstone in 1837, was the first telegraph implementation to be put into commercial service.

Many arrangements came before and after, but this one dominated for several reasons. Most importantly, it was incredibly simple. All you needed at each end was a key—essentially a switch—a sounder, an electromagnet that makes clicking noises, a single wire, and a battery. The earth was used as a second wire to complete the battery circuit. That simplicity meant it did not cost much to set up, and it was extremely reliable.

Once the basic system was in place, networks rapidly developed. The single wire had to go somewhere, and poles with glass insulators were the preferred place because they were inexpensive and easy to build. The poles went up along railroad tracks because it was an easy place to put them. Most train stations therefore had a telegraph office, and anyone in a town with a telegraph station could communicate with the rest of the world.

Imagine what would happen to a civilization that suddenly, for the first time, had the easy ability to communicate over long distances. A message that might have taken several days or a week to get through by letter on horseback could now get through in a minute.

During the Civil War, for example, the telegraph was a huge game changer for the North because messages could get to and from many battlefields almost instantly. President Lincoln himself could be found in the telegraph office getting instant information. It was much easier to move troops and supplies around with good communications in place.

Engineers found ways to insulate wires with gutta-percha and undersea telegraph cables soon followed. Engineers shrank the world.

SEE ALSO Olmec Compass (c. 1000 BCE) Telephone (1876), Radio Station (1920), ARPANET (1969).

A telegraph key. The telegraph represented an unprecedented ability to communicate over long distances.

1839

Daguerreotype • *Derek B. Lowe*

Nicéphore (**Joseph**) **Niépce** (1765–1833), **Louis-Jacques-Mandé Daguerre** (1787–1851)

The most famous form of applied photochemistry is photography. Adapting the camera obscura—a mechanical method of projecting an image using light, lenses, and mirrors—French inventor Nicéphore Niépce attempted to use chemicals to record what formerly required an artist's eye and hand. In a process he called *heliography* (sun writing), Niépce coated a metal plate with the photosensitive agent bitumen (a tarry, naturally occurring petroleum fraction), positioned the plate in a camera obscura to receive the reflected image, and exposed it to sunlight for hours. Brightly lit areas hardened in the sun (probably via a free radical–induced polymerization), and unhardened, shaded areas were then washed away with a solvent, producing in 1826 the first permanent photographs. But because it required long hours of exposure, the technique was not a practical one.

French artist and photographer Louis-Jacques-Mandé Daguerre, who had been collaborating with Niépce, carried on after Niépce’s death, using as a light-sensitive agent the more promising silver compounds. After much experimentation, Daguerre produced metal plates coated with silver iodide, so light sensitive that several minutes of exposure were enough to produce an image. The plate was developed by exposure to mercury vapors, and the resulting image was composed of dark silver-mercury alloy (amalgam). But the plate was still light sensitive, and the unreacted silver iodide had to be removed to make the image permanent. Daguerre soon found that the final images could be tinted attractively (and made more durable) by a final exposure to gold salts.

The daguerreotype, revealed in 1839, was a sensation, especially when the process had improved enough for human portraiture. Still, the exposure times —between ten and sixty seconds—tended to produce rather a rather stiff appearance in the subjects, even under the best conditions. The whole procedure was difficult, expensive, and toxic. But it was the first, and it changed the world.

SEE ALSO Eyeglasses (1284), Telescope (1608), Hologram (1947).

LEFT: *A daguerreotype of Daguerre himself, 1844.* RIGHT: *Foremen of the Phoenix Fire Company and the Mechanic Fire Company in Charleston, South Carolina, c. 1855.*

1839

Rubber • *Derek B. Lowe*

Thomas Hancock (1786–1865), **Charles Goodyear** (1800–1860)

Rubber, a well-known example of a natural polymer, is built from molecules of isoprene, a five-carbon compound found in a variety of plants that is believed to protect them from heat stress. When isoprene is polymerized, the first product created is the sticky latex sap given off by plants such as the South American rubber tree.

This sap can be processed further to natural rubber—as it has been for hundreds of years in Central and South America—but natural rubber has a lot of limitations, among them its relentless stickiness in hot weather and its propensity to crack in the cold. Many inventors tinkered with it, trying to turn it into something more useful, and after many impoverished years of experimentation, American chemist Charles Goodyear famously succeeded. With the addition of sulfur and heat, he discovered, whether by accident or by design (one version has him sticking a lump of rubber to a hot stove), the rubber was cured into an elastic, durable, nonsticky substance that looked as if it would have huge potential, if it could be made industrially. More years of experimentation followed, with Goodyear stretching the patience of his family and his creditors. By 1844 he had filed for a patent for what would come to be known as the vulcanization (after the Roman god of fire) of rubber and had built a factory to produce goods made from it. There were still many wild swings in his fortunes as he fought patent disputes in Europe, most notably with English manufacturing engineer Thomas Hancock, who was simultaneously experimenting with rubber and had received a British patent for the same process.

Chemically, the sulfur in vulcanized rubber crosslinks the polymer chains, altering the properties of the material by changing the ways that the molecules can move relative to each other. Serendipitous or not, the vulcanization of rubber was a significant industrial and commercial advance, and today is responsible for consumer goods as varied as tires, hoses, shoe soles, and hockey pucks, as well as many parts of the industrial machinery involved in making them.

SEE ALSO Plastic (1856), Polyethylene (1933), Photosynthesis (1947).

Rubber-tree sap, harvested the old-fashioned way.

1841

Fiber Optics • *Clifford A. Pickover*

Jean-Daniel Colladon (1802–1893), **Charles Kuen Kao** (b. 1933), **George Alfred Hockham** (b. 1938)

The science of fiber optics has a long history, including such wonderful demonstrations as Swiss physicist Jean-Daniel Colladon's light fountains in 1841, in which light traveled within an arcing stream of water from a tank. Modern fiber optics—discovered and independently refined many times through the 1900s—use flexible glass or plastic fibers to transmit light. In 1957, researchers patented the fiberoptic endoscope to allow physicians to view the upper part of the gastrointestinal tract. In 1966, electrical engineers Charles K. Kao and George A. Hockham suggested using fibers to transmit signals, in the form of light pulses, for telecommunications.

Through a process called *total internal reflection*, light is trapped within the fiber as a result of the higher refractive index of the core material of the fiber relative to that of the thin cladding that surrounds it. Once light enters the fiber's core, it continually reflects off the core walls. The signal propagation can suffer some loss of intensity over very long distances, and thus it may be necessary to boost the light signals using optical regenerators. Today, optical fibers have many advantages over traditional copper wires for communications. Signals travel along relatively inexpensive and lightweight fibers with less attenuation, and they are not affected by electromagnetic interference. Also, fiber optics can be used for illumination or transferring images, thus allowing illumination or viewing of objects that are in tight, difficult-to-reach places.

In optical-fiber communications, each fiber can transmit many independent channels of information via different wavelengths of light. The signal may start as an electronic stream of bits that modulates lights from a tiny source, such as a light-emitting diode or laser diode. The resultant pulses of infrared light are then transmitted. In 1991, technologists developed photonic-crystal fibers that guide light by means of diffraction effects from a periodic structure such as an array of cylindrical holes that run through the fiber.

SEE ALSO Newton's Prism (1672), Wave Nature of Light (1801), Laser (1960).

Optical fibers carry light along their lengths. Through a process called total internal reflection, light is trapped within the fiber until it reaches the end of the fiber.

1842

General Anesthesia • *Clifford A. Pickover*

Frances Burney (1752–1840), **Johann Friedrich Dieffenbach** (1795–1847), **Crawford Williamson Long** (1815–1878), **Horace Wells** (1815–1848), **William Thomas Green Morton** (1819–1868)

In our modern world, we are likely to forget the horrifying realities of surgery before anesthesia. Fanny Burney, a famous nineteenth-century novelist and playwright, recounts the mastectomy she endured with only a glass of wine for the pain. Seven males held her down as the surgery began. She writes, “When the dreadful steel was plunged into the breast—cutting through veins-arteries-flesh-nerves—I needed no injunction not to restrain my cries. I began a scream that lasted unintermittently during the whole time of the incision. . . . Oh Heaven!—I then felt the knife racking against the breast bone—scraping it! This was performed while I yet remained in utterly speechless torture.”

General anesthesia is a state of unconsciousness induced by drugs, allowing a patient to undergo surgery without pain. Early forms of anesthesia date back to prehistoric times in the form of opium. Inca shamans used coca leaves to locally numb a site on the body. However, the discovery of general anesthesia suitable for modern operations is often attributed to three Americans: physician Crawford W. Long and dentists Horace Wells and William Morton. In 1842, Long removed a neck cyst while the patient inhaled ether, an anesthetic gas. In 1844, Wells extracted many teeth using nitrous oxide, commonly known as laughing gas. Morton is famous for his public demonstration of the use of ether in 1846 to assist a surgeon in removing a tumor from a patient’s jaw, and newspapers carried the story. In

1847, chloroform was also used, but it had higher risks than ether. Safer and more effective drugs are used today.

After Morton's demonstrations, the use of anesthetics began to spread rapidly. In 1847, Johann Friedrich Dieffenbach, a pioneer in plastic surgery, wrote, "The wonderful dream that pain has been taken away from us has become reality. Pain, the highest consciousness of our earthly existence, the most distinct sensation of the imperfection of our body, must now bow before the power of the human mind, before the power of ether vapor."

SEE ALSO Sutures (c. 3000 BCE) Paré's "Rational Surgery" (1545), Heart Transplant (1967).

Three medical gases on a surgical room machine. Nitrous oxide (N_2O) is sometimes used as a carrier gas in a 2:1 ratio with oxygen for more powerful general anesthesia drugs, such as desflurane or sevoflurane.

3
2
1,5
N2 O
200
100
AIR
3
2
1,5
AIR
200
100
O2
3
2
1,5
O2
N2O
AIR
O2

1843

Conservation of Energy • *Clifford A. Pickover*

James Prescott Joule (1818–1889)

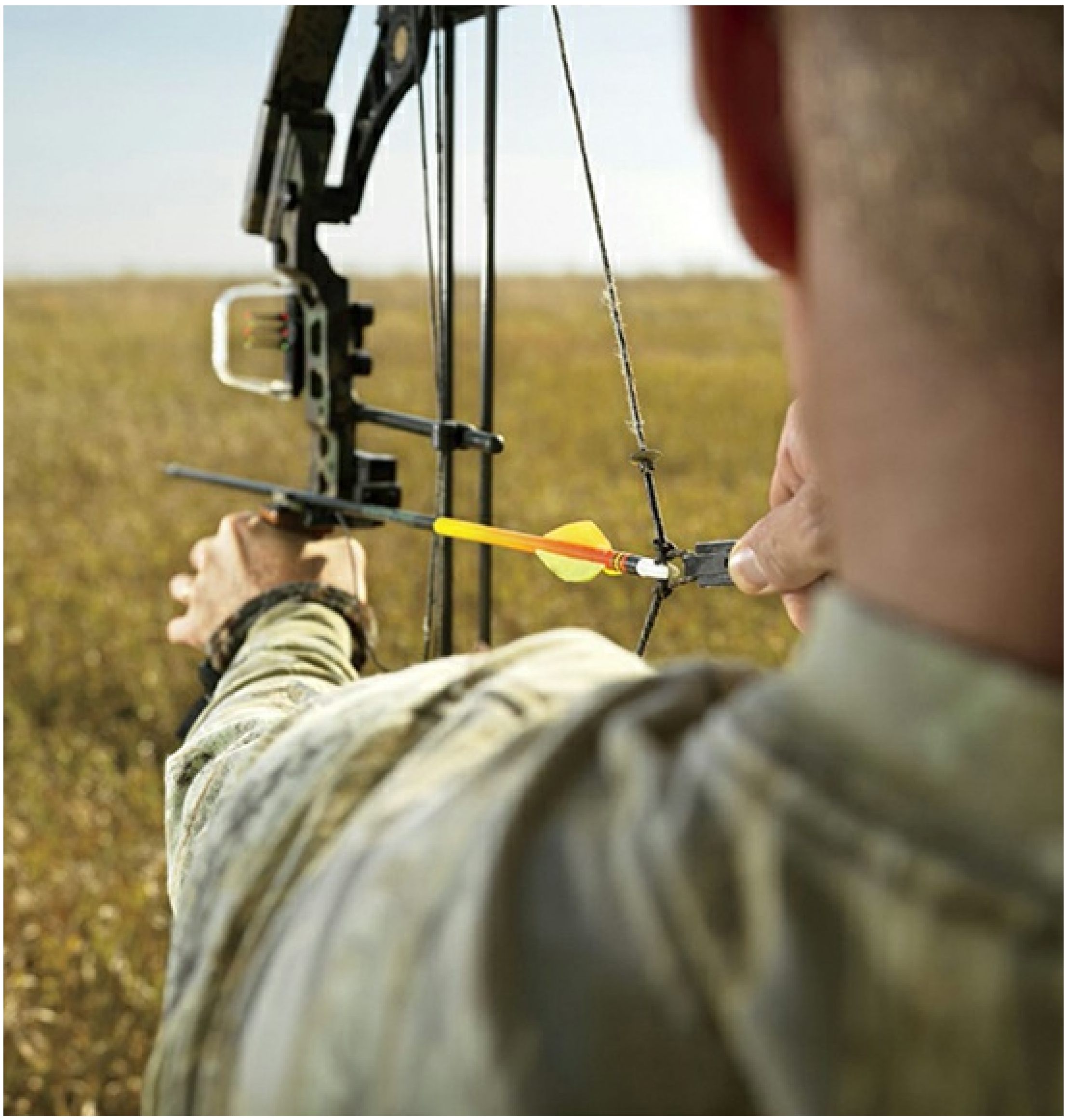
"The law of the conservation of energy offers . . . something to clutch at during those late-night moments of quiet terror, when you think of death and oblivion," writes science-journalist Natalie Angier. "Your private sum of *E*, the energy in your atoms and the bonds between them, will not be annihilated. . . . The mass and energy of which you're built will change form and location, but they will be here, in this loop of life and light, the permanent party that began with a Bang."

Classically speaking, the principle of the conservation of energy states that the energy of interacting bodies may change forms but remains constant in a closed system. Energy takes many forms, including kinetic energy (energy of motion), potential energy (stored energy), chemical energy, and energy in the form of heat. Consider an archer who deforms, or strains, a bow. This potential energy of the bow is converted into kinetic energy of the arrow when the bow is released. The total energy of the bow and arrow, in principle, is the same before and after release. Similarly, chemical energy stored in a battery can be converted into the kinetic energy of a turning motor. The gravitational potential energy of a falling ball is converted into kinetic energy as it falls. One key moment in the history of the conservation of energy was physicist James Joule's 1843 discovery of how gravitational energy (lost by a falling weight that causes a water paddle to rotate) was equal to the thermal energy gained by water due to friction with the paddle. The First Law of Thermodynamics is often stated as: The increase in internal energy of a system due to heating is equal to the amount of energy added by heating, minus the work performed by the system on its surroundings.

Note that in our bow and arrow example, when the arrow hits the target, the kinetic energy is converted to heat. The Second Law of Thermodynamics limits the ways in which heat energy can be converted into work.

SEE ALSO Second Law of Thermodynamics (1850), *E* = *mc*² (1905), Energy from the Nucleus (1942).

This potential energy of the strained bow is converted to kinetic energy of the arrow when the bow is released. When the arrow hits the target, the kinetic energy is converted to heat.



1844

Transcendental Numbers • *Clifford A. Pickover*

Joseph Liouville (1809–1882), **Charles Hermite** (1822–1901), **Ferdinand von Lindemann** (1852–1939)

In 1844, French mathematician Joseph Liouville considered the following interesting number: 0.110001000000000000000001000. . ., known today as the Liouville constant. Can you guess its significance or what rule he used to create it?

Liouville showed that his unusual number was transcendental, thus making this number among the first to be proven transcendental. Notice that the constant has 1 in each decimal place corresponding to a factorial, and zeros elsewhere. This means that the 1s occur only in the 1st, 2nd, 6th, 24th, 120th, 720th, etc. places.

Transcendental numbers are so exotic that they were only “discovered” relatively recently in history, and you may only be familiar with one of them, π, and perhaps Euler’s Number, e. These numbers cannot be expressed as the root of any algebraic equation with rational coefficients. This means, for example, that π could not exactly satisfy equations like $2x^4 - 3x^2 + 7 = 0$.

Proving that a number is transcendental is difficult. French mathematician Charles Hermite proved *e* was transcendental in 1873, and German mathematician Ferdinand von Lindemann proved π was transcendental in 1882. In 1874, German mathematician Georg Cantor surprised many mathematicians by demonstrating that “almost all” real numbers are transcendental. Thus, if you could somehow put all the numbers in a big jar, shake the jar, and pull one out, it would be virtually certain to be transcendental. Yet despite the fact that transcendental numbers are "everywhere," only a few are known and named. There are lots of stars in the sky, but how many can you name?

Aside from his mathematical pursuits, Liouville was interested in politics and was elected to the French Constituting Assembly in 1848. After a later election defeat, Liouville became depressed. His mathematical ramblings became interspersed with poetical quotes. Nonetheless, during the course of his life, Liouville wrote more than 400 serious mathematical papers.

SEE ALSO π (c. 250 BCE), Euler's Number, *e* (1727), Cantor's Transfinite Numbers (1874).

French mathematician Charles Hermite, c. 1887. Hermite proved in 1873 that Euler's number e was transcendental.

1847

Semmelweis’s Hand Washing • *Clifford A. Pickover*

Ignaz Philipp Semmelweis (1818–1865), Louis Pasteur (1822–1895), Sir Joseph Lister (1827–1912)

Authors K. Codell Carter and Barbara Carter write, “Medical advances are purchased by two kinds of sacrifice: the sacrifice of researchers trying to understand disease and the sacrifice of patients who die or are killed in the process. [One] particular advance was purchased, in part, by the sacrifice of hundreds of thousands of young women who died, following childbirth, of a terrible disease known as childbed fever—a disease that was rampant in the charity maternity clinics of the early nineteenth century.”

Although several physicians had suggested the value of cleanliness in preventing infection even before microorganisms were discovered as causes of disease, the individual most famous for early systematic studies of disinfection was the Hungarian obstetrician Ignaz Semmelweis. Semmelweis noticed that the Vienna hospital in which he worked had a much higher rate of maternal mortality due to childbed fever than a similar hospital. He also noted that only in his hospital did physicians routinely study cadavers before examining patients.

Childbed fever, also known as puerperal fever, is a form of bacteria-caused sepsis informally referred to as blood poisoning. Semmelweis also noticed that puerperal fever was rare among women who gave birth in the streets, and he surmised that infectious substances (e.g., particles of some kind) were being passed from cadavers to the women. After instructing hospital staff to always wash their hands in a chlorinated disinfecting solution before treating women, the number of deaths plummeted dramatically.

Alas, despite his amazing results, many of the physicians of the time did not accept his findings, perhaps in part because this would have been admitting that they were the unwitting cause of so much death. Additionally, many physicians of the time blamed such diseases on miasma, a kind of toxic atmosphere. In the end, Semmelweis went mad and was involuntarily confined to an insane asylum, where he was beaten to death by guards. After his death, however, he was vindicated by the germ studies of French microbiologist Louis Pasteur and innovations in antiseptic surgery by British surgeon Joseph Lister.

SEE ALSO Sewage Systems (c. 600 BCE) Germ Theory of Disease (1862), Antiseptics (1865).

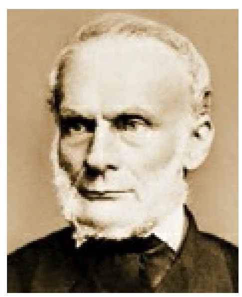
Today, when surgeons scrub their hands before an operation, it is common to use a sterile brush, chlorhexidine or iodine wash, and a tap that can be turned on and off without hand intervention.

1850

Second Law of Thermodynamics •

Clifford A. Pickover

Rudolf Clausius (1822–1888), **Ludwig Boltzmann** (1844–1906)



Whenever I see my sand castles on the beach fall apart, I think of the *Second Law of Thermodynamics* (SLT). The SLT, in one of its early formulations, states that the total entropy, or disorder, of an isolated system tends to increase as it approaches a maximum value. For a closed thermodynamic system, entropy can be thought of as a measure of the amount of thermal energy unavailable to do work. German physicist Rudolf Clausius stated the First and Second Laws of Thermodynamics in the following form: The energy of the universe is constant, and the entropy of the universe tends to a maximum.

Thermodynamics is the study of heat, and more generally the study of transformations of energy. The SLT implies that all energy in the universe tends to evolve toward a state of uniform distribution. We also indirectly invoke the SLT when we consider that a house, body, or car—without maintenance—deteriorates over time. Or, as novelist William Somerset

Maugham wrote, “It’s no use crying over spilt milk, because all of the forces of the universe were bent on spilling it.”

Early in his career, Clausius stated, “Heat does not transfer spontaneously from a cool body to a hotter body.” Austrian physicist Ludwig Boltzmann expanded upon the definition for entropy and the SLT when he interpreted entropy as a measure of the disorder of a system due to the thermal motion of molecules.

From another perspective, the SLT says that two adjacent systems in contact with each other tend to equalize their temperatures, pressures, and densities. For example, when a hot piece of metal is lowered into a tank of cool water, the metal cools and the water warms until each is at the same temperature. An isolated system that is finally at equilibrium can do no useful work without energy applied from outside the system, which helps explain how the SLT prevents us from building many classes of Perpetual Motion Machines.

SEE ALSO Boltzmann’s Entropy Equation (1875), Carnot Engine (1824), Conservation of Energy (1834).

LEFT: *Rudolph Clausius.* RIGHT: *Microbes build their “improbable structures” from ambient disordered materials, but they do this at the expense of increasing the entropy around them. The overall entropy of closed systems increases, but the entropy of individual components of a closed system may decrease.*

1855

Bessemer Process • *Marshall Brain*

Henry Bessemer (1813–1898)

In the Iron Age, the prevalent use of iron implements changed the world. However, an equally revolutionary shift occurred after English engineer Henry Bessemer developed a process to refine iron and produce steel commercially, first patented in 1855.

Where does steel come from? Start with iron. Dig iron ore out of the ground and transform it into iron in a blast furnace. It comes out as pig iron with a carbon content of 5 percent or so. Put pig iron into a basic oxygen furnace to form steel. Pure oxygen blasts in under pressure and burns off much of the carbon, leaving behind 0.1 percent carbon (mild steel) to 1.25 percent carbon (high-carbon steel). The carbon content, plus any alloying metals, plus the quenching process, determine the properties of the steel in use.

Steel is a remarkable material: dependably strong and resistant to fatigue, it is also workable and highly mutable—it can take a number of different forms. For example, if you heat up steel and quench (cool) it one way, it is more ductile. Quench it another way and it is much harder and more brittle. It is even possible to get both effects at the same time with *case hardening*. The outer shell is hard and therefore difficult to cut, while the interior is softer to combat the brittleness.

Then there are the alloys. Add a little chromium to steel and it won't rust. Add extra carbon and it becomes much harder. Add tungsten or molybdenum and you get tool steels. Add vanadium and it holds up better to wear.

This combination of advantages explains why steel is so ubiquitous. Engineers use steel in car bodies and engines because of the combination of strength, cost, and durability. Engineers use steel in skyscrapers such as Burj Khalifa for the same reasons. Big bridges such as the Millau Viaduct, same thing. They reinforce concrete with steel to greatly improve its strength in tension. One place where steel isn't found is where weight is a factor—aluminum or carbon fiber is used there. Or where strength and durability isn't a big factor and cost is—plastic is used there.

SEE ALSO Iron Smelting (c. 1300 BCE), Roman Concrete (c. 126), Plastic (1856)

White-hot steel pours like water from a 35-ton electric furnace, Allegheny Ludlum Steel Corp., Brackenridge, PA, circa 1941.

1855

Cell Division • *Clifford A. Pickover*

Matthias Jakob Schleiden (1804–1881), Theodor Schwann (1810–1882), Rudolf Ludwig Karl Virchow (1821–1902)

Based on his observations and theories, German physician Rudolf Virchow emphasized that diseases could be studied not only by observing a patient's symptoms but by realizing that all pathology (disease diagnosis) is ultimately a study of cells. Rather than focusing on the entire body, he helped to launch the field of cellular pathology by considering that certain cells or groups of cells can become sick.

In 1855, he popularized the famous aphorism *omnis cellula e cellula*, which means that every cell derives from a preexisting cell. This suggestion was a rejection of the theory of spontaneous generation, which posited that cells and organisms could arise from inanimate matter. Virchow's microscopic studies revealed cells dividing into two equal parts, which contributed to the cell theory, the other tenets of which posited that all living things are made of one cell or more, and that cells are the basic units of life. Other famous contributors to the cell theory were German physiologist Theodor Schwann and German botanist Matthias Jakob Schleiden. One of Virchow's famous phrases was "The task of science is to stake out the limits of the knowable, and to center consciousness within them."

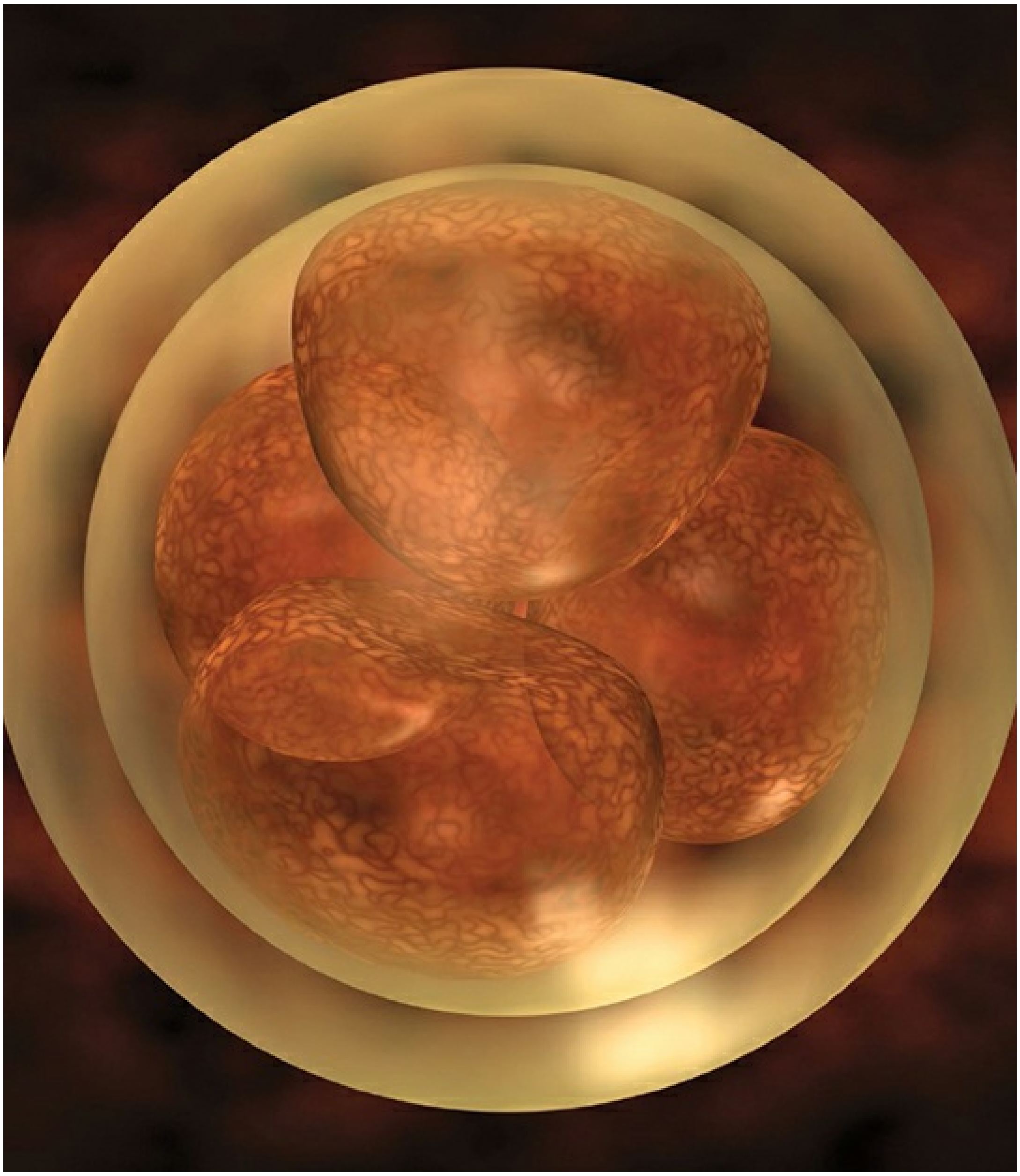
As well as describing cell division, Virchow was the first to accurately identify leukemia cells in blood cancer. Despite these accomplishments, he rejected the notion that bacteria can cause disease, as well as the value of cleanliness in preventing infection. He also rejected the germ theory of

Pasteur, believing that diseased tissues were caused by a malfunctioning of cells and not from an invasion of a foreign microbe.

Science writer John G. Simmons notes, “With the cellular hypothesis, Virchow expanded the research horizons of biochemistry and physiology and had great influence in the broader field of biology, where the cell doctrine eventually evolved in molecular biology, as genetics evolved and reproduction became better understood.” Today, we know that cancers result from uncontrolled cell divisions and that skin cells that heal a wound are created from preexisting, dividing skin cells.

SEE ALSO Causes of Cancer (1761), Semmelweis’s Hand Washing (1847), Germ Theory of Disease (1862), HeLa Cells (1951), Telomerase (1984).

Artistic representation of a zygote after two cell-division steps. The zygote is the initial cell formed when a new organism is produced by the union of a sperm and an egg.



1856

Plastic • *Marshall Brain*

Alexander Parkes (1813–1890)

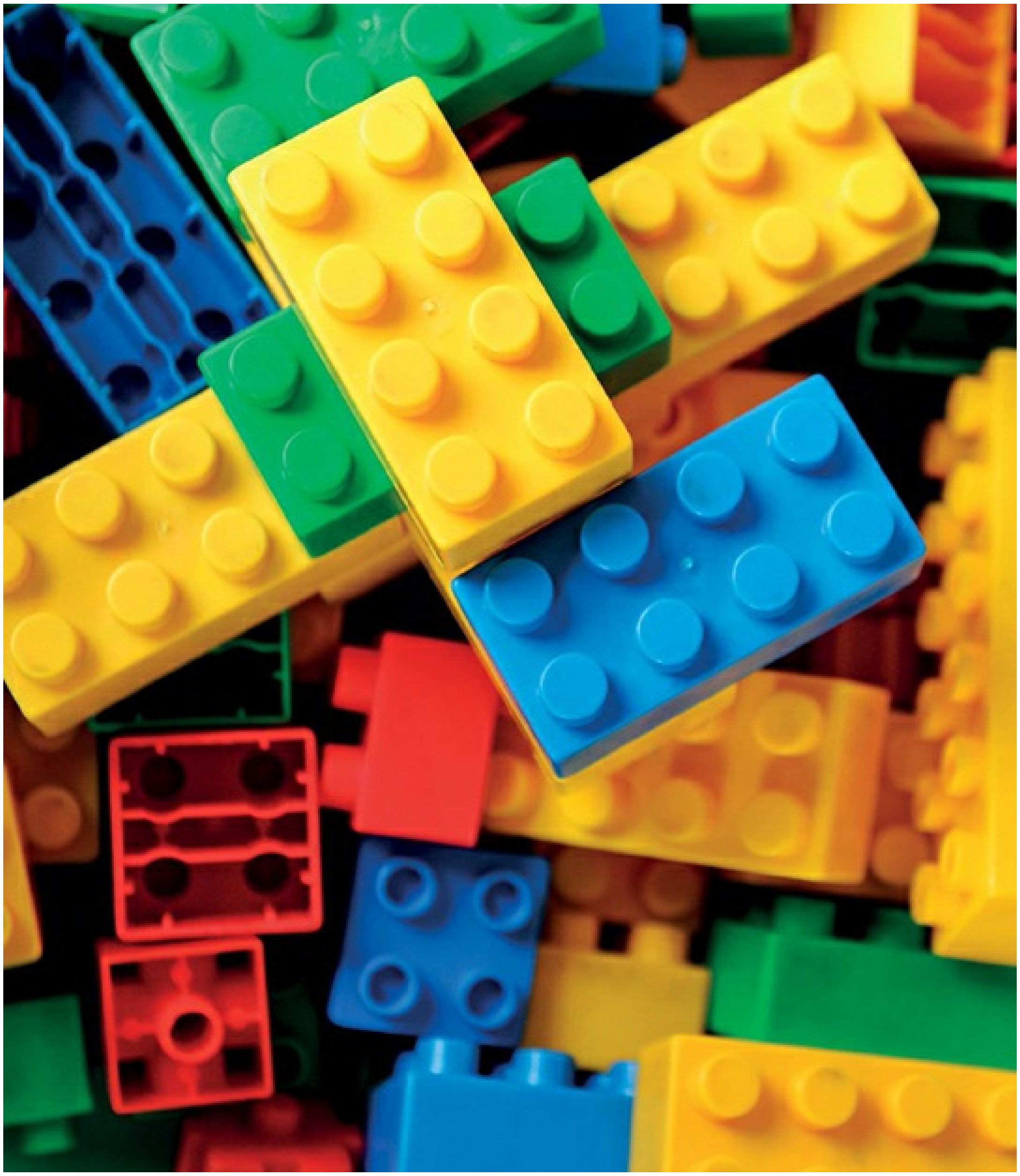
Although humans have used naturally occurring plastics such as rubber and collagen for millennia, the first manmade plastic was Parkesine, patented by Alexander Parkes in 1856. Today, the amount of plastic that surrounds us is nearly indescribable. The affordability, malleability, and durability of plastic makes it an ideal material.

One reason for the widespread use of plastic is the work of chemical engineers, who have used mass-scale processes in factories to make the production of plastic so inexpensive. Another factor is the contribution of mechanical engineers and industrial engineers who design the parts and create the molding systems to produce shaped plastic objects. Plastic is also lightweight, strong for its weight, corrosion-free, easily molded, and it comes in so many forms with many different properties. While Parkesine, made of cellulose, was often used to create synthetic ivory, modern plastics are normally made of other, higher-quality components. Polyethylene is made of long chains of carbon and hydrogen atoms, so it is essentially solidified gasoline. The length of the chains, the amount of branching, and the amount of polymerization gives polyethylene its many different properties.

Engineers and scientists have worked together to create hundreds of other types of plastics as well. Some plastics form fibers that become soft cloth or pillow stuffing. Nylon fibers, produced by Wallace Carothers at Dupont in 1935, create a strong, abrasion-resistant fabric for parachutes, backpacks, and tents. Kevlar was developed later, and is strong enough for use in bulletproof vests. Some plastics are rubbery and they become seals, gaskets, O-rings, wheels, and grips. Some plastics are clear like glass; others are completely opaque. Some are so strong that they replicate the tensile strength of steel while being flexible and light. This diversity and versatility means that engineers can use plastics to make almost anything.

SEE ALSO Roman Concrete (c. 126), Rubber (1839), Polyethylene (1933).

Plastic toy blocks of this sort are often made out of ABS (acrylonitrile butadiene styrene) plastic.



1858

Möbius Strip • *Clifford A. Pickover*

August Ferdinand Möbius (1790–1868)

German mathematician August Ferdinand Möbius was a shy, unsociable, absentminded professor whose most famous discovery, the Möbius strip, was made when he was almost seventy years old. To create the strip yourself, simply join the two ends of a ribbon after giving one end a 180-degree twist with respect to the other end. The result is a one-sided surface—a bug can crawl from any point on such a surface to any other point without ever crossing an edge. Try coloring a Möbius strip with a crayon. It's impossible to color one side red and the other green because the strip has only one side.

Years after Möbius's death, the popularity and applications of the strip grew, and it has become an integral part of mathematics, magic, science, art, engineering, literature, and music. The Möbius strip is the ubiquitous symbol for recycling where it represents the process of transforming waste materials into useful resources. Today, the Möbius strip is everywhere, from molecules and metal sculptures to postage stamps, literature, technology patents, architectural structures, and models of our entire universe.

August Möbius had simultaneously discovered his famous strip with a contemporary scholar, the German mathematician Johann Benedict Listing (1808–1882). However, Möbius seems to have taken the concept a little further than Listing, as Möbius more closely explored some of the remarkable properties of this strip.

The Möbius strip is the first one-sided surface discovered and investigated by humans. It seems far-fetched that no one had described the properties of one-sided surfaces until the mid-1800s, but history has recorded no such observations. Given that the Möbius strip is often the first and only exposure of a wide audience to the study of topology—the science of geometrical shapes and their relationships to one another—this elegant discovery deserves a place in this book.

SEE ALSO Platonic Solids (c. 350 BCE), Euclid's *Elements* (c. 300 BCE), Non-Euclidean Geometry (1829), Tesseract (1888)

Multiple Möbius strips, an artwork created by Teja Kraˇsek and Cliff Pickover. The Möbius strip is the first one-sided surface discovered and investigated by humans.

1859

Darwin’s Theory of Natural Selection

• Michael C. Gerald with Gloria E. Gerald

Charles Lyell (1797–1875), **Thomas Malthus** (1766–1834), **Charles Darwin** (1809–1882), **Alfred Russel Wallace** (1823–1913)

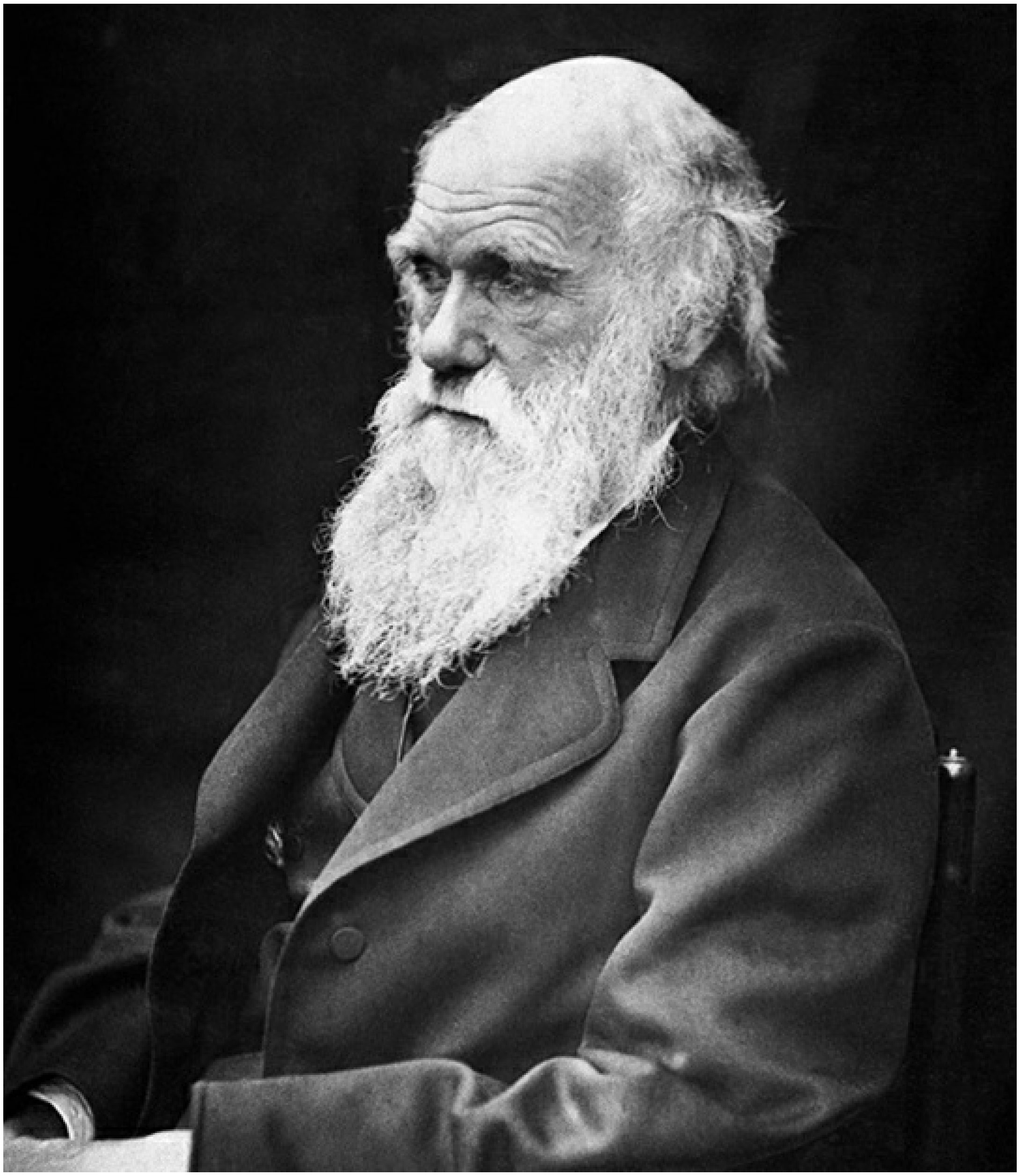
On the Origin of Species by Means of Natural Selection was over twenty years in its formulation and was based on a number of disparate sources and observations that Charles Darwin had the genius to integrate. While sailing on the HMS *Beagle* (1831–1835), he read *Principles of Geology*, wherein Charles Lyell proposed that the fossils embedded in rock were imprints of living beings millions of years old that no longer inhabited the earth nor resembled extant beings. In 1838, Darwin read Thomas Malthus’s *An Essay on the Principle of Population*, in which Malthus postulated that the rate of growth of the population was far exceeding the food supply and that, if unchecked, would have catastrophic consequences. Darwin also considered the practice of farmers who selected their best animal stock for breeding (artificial selection). The fourteen finches he found on the Galápagos Islands were similar in all respects, with the exception of the size and shape of their beaks, which were adapted to the available supply of food on their island.

Darwin was not the first to conceive of evolution, but the others lacked a coherent theory to explain its occurrence. His theory was based on natural selection. In nature, there is competition within the species for the limited resources. Those living beings that have the most favorable traits that are best adapted to their environments are most likely to survive and reproduce and pass their favorable traits on to offspring. Thus, over many generations, the species that has arisen from a common ancestor “descends with modifications.”

In the 1840s, Darwin sketched the outline of his natural selection theory in an essay. Anticipating a storm of protest to greet his anti-Creation theory, he hesitated to go public but, over the next decade, continued to gather additional evidence to bolster it. In 1858, Darwin learned that a fellow naturalist, Alfred Russel Wallace, had independently developed a theory of natural selection that was strikingly similar to his own. Darwin rapidly completed his book, *Origin of Species*, which appeared in 1859 and proved to be a runaway best seller and a classic in scientific literature.

SEE ALSO Agriculture (c. 10,000 BCE), Linnaean Classification of Species (1735), Artificial Selection (Selective Breeding) (1760), Darwin and the Voyages of the *Beagle* (1831), Fossil Record and Evolution (1836), Ecological Interactions (1859)

An 1869 photograph of Charles Darwin taken by Julia Margaret Cameron (1815–1879), who was known for her photographs of British celebrities.



1859

Ecological Interactions • *Michael C. Gerald with Gloria E. Gerald*

Charles Darwin (1809–1882)

Ecology examines the relations between living organisms and their environment, and it is not surprising that the relationship between or among species sharing the same ecosystem affects one another. At one end, the nature of this interaction can benefit one species at the expense of the other, to the other extreme each can benefit from the interaction. In his *Origin of Species* (1859), Darwin noted that the struggle for survival was greatest among members of the same species because they possess similar phenotypes and niche requirements.

WHAT'S IN A RELATIONSHIP? Predation and parasitism are situations in which only one species profits from the interaction, while another species pays the price. Predation represents the ultimate extreme of an ecological interaction, in which one species captures and feeds on another, as an owl kills a field mouse or the carnivorous pitcher plant catches insects. In a somewhat less extreme instance—parasitism—one species (the parasite) benefits at the expense of the other (host), which derives no benefit from the interaction, as when tapeworms inhabit the intestines of a vertebrate host. Intracellular parasites, such as protozoa or bacteria, often rely upon a vector to transport the parasite to its host; the anopheles mosquito conveys the malaria-carrying protozoan parasite to its human host, for example.

In commensalism, one species receives benefit from another, which does not suffer adversely from the interplay. The remora, a tropical open-ocean-dwelling fish, lives symbiotically with sharks and eats the shark's leftover food. The fierasfer is a small, slender fish that lives inside the cloacal cavity (the lower end of the alimentary canal) of the sea cucumber to protect itself from predators.

The most equitable of all interactions is mutualism, in which each species provides resources or services to the other resulting in mutual benefit. Lichen is a plant that results when a green alga lives symbiotically with a fungus, where the fungus gains oxygen and carbohydrate from the alga, which reciprocally obtains water, carbon dioxide, and mineral salts from the fungus.

SEE ALSO Nitrogen Cycle and Plant Chemistry (1837), Darwin's Theory of Natural Section (1859), Food Webs (1927)

In this example of mutualism, a cleaner shrimp is cleaning parasites from the mouth of a moray eel. The fish benefits by having the parasites removed, and the shrimp gains the nutritional value of the parasites.

1859

Kinetic Theory • *Clifford A. Pickover*

James Clerk Maxwell (1831–1879), **Ludwig Eduard Boltzmann** (1844–1906)

Imagine a thin plastic bag filled with buzzing bees, all bouncing randomly against one another and the surface of the bag. As the bees bounce around with greater velocity, their hard bodies impact the wall with greater force, causing it to expand. The bees are a metaphor for atoms or molecules in a gas. The kinetic theory of gases attempts to explain the macroscopic properties of gases—such as pressure, volume, and temperature—in terms of the constant movements of such particles.

According to kinetic theory, temperature depends on the speed of the particles in a container, and pressure results from the collisions of the particles with the walls of the container. The simplest version of kinetic theory is most accurate when certain assumptions are fulfilled. For example, the gas should be composed of a large number of small, identical particles moving in random directions. The particles should experience elastic collisions with themselves and the container walls but have no other kinds of forces among them. Also, the average separation between particles should be large.

Around 1859, physicist James Clerk Maxwell developed a statistical treatment to express the range of velocities of gas particles in a container as a function of temperature. For example, molecules in a gas will increase speed as the temperature rises. Maxwell also considered how the viscosity and diffusion of a gas depend on the characteristics of the molecules' motion. Physicist Ludwig Boltzmann generalized Maxwell's theory in 1868, resulting in the Maxwell-Boltzmann distribution law, which describes a probability distribution of particle speeds as a function of temperature. Interestingly, scientists still debated the existence of atoms at this time.

We see the kinetic theory in action in our daily lives. For example, when we inflate a tire or balloon, we add more air molecules to the enclosed space, which results in more collisions of the molecules on the inside of the enclosed space than there are on the outside. As a result, the enclosure expands.

SEE ALSO Atomic Theory (1808), Brownian Motion (1827), Boltzmann's Entropy Equation (1875)

According to kinetic theory, when we blow a soap bubble, we add more air molecules to the enclosed space, leading to more molecular collisions on the bubble's inside than on the outside, causing the bubble to expand.

1859

Riemann Hypothesis • *Clifford A. Pickover*

Georg Freidrich Bernhard Riemann (1826–1866)

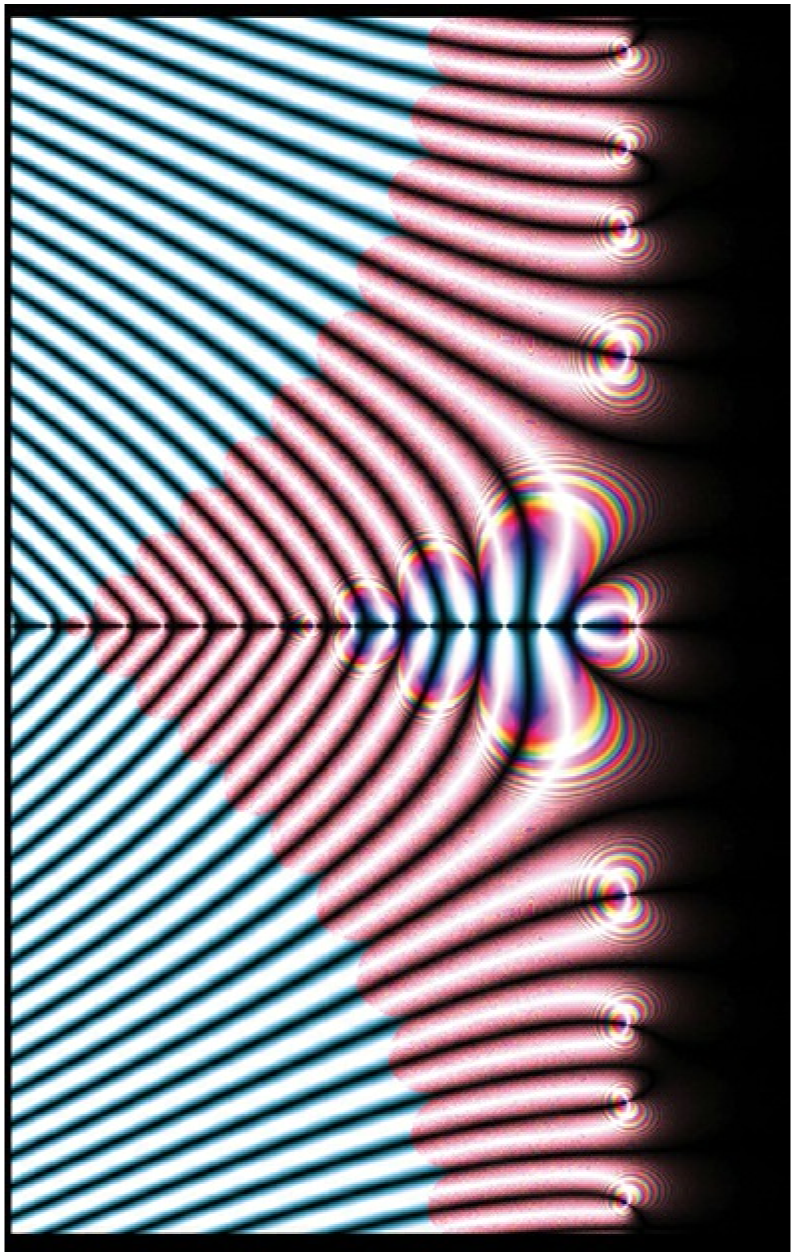
Many mathematical surveys indicate that the "proof of the Riemann hypothesis" is the most important open question in mathematics. The proof involves the *zeta function*, which can be represented by a complicated-looking curve that is useful in number theory for investigating properties of prime numbers. Written as $\zeta(x)$, the function was originally defined as the infinite sum $\zeta(x) = 1 + (1/2)^x + (1/3)^x + (1/4)^x + \ldots$ etc. When $x = 1$, this series has no finite sum. For values of x larger than 1, the series adds up to a finite number. If x is less than 1, the sum is again infinite. The complete zeta function, studied and discussed in the literature, is a more complicated function that is equivalent to this series for values of x greater than 1, but has finite values for any real or complex number, except for when the real part is equal to 1. We know that the function equals zero when x is −2, −4, −6,. . . and that the function has an infinite number of zero values for the set of complex numbers, the real part of which is between zero and one—but we do not know exactly for what complex numbers these zeros occur. Mathematician Georg Bernhard Riemann conjectured that these zeros occur for those complex numbers the real part of which equals 1/2. Although vast numerical evidence exists that favors this conjecture, it is still unproven. The proof of Riemann's hypothesis would have profound consequences for the theory of prime numbers and in our understanding of the properties of complex numbers. Amazingly, physicists may have found a mysterious connection between quantum physics and number theory through investigations of the Riemann Hypothesis.

Around the year 2005, over 11,000 volunteers worldwide worked on the

Riemann Hypothesis, using a distributed computer software package, as part of project ZetaGrid, to search for the zeros of the Riemann zeta function. More than 1 billion zeros for the zeta function were calculated every day. The investigators found no counterexample to the Riemann hypothesis.

SEE ALSO Sieve of Eratosthenes (c. 240 BCE) Imaginary Numbers (1572), Hilbert's 23 Problems (1900), Proof of the Kepler Conjecture (2017).

Tibor Majlath's rendition of the Riemann zeta function ζ(s) in the complex plane. The four small bulls-eye patterns at top and bottom correspond to zeros at Re(s) = ½. The plot extends from −32 to +32 in the real and imaginary directions.



1861

Cerebral Localization • *Clifford A. Pickover*

Hippocrates of Cos (460 BCE–377 BCE), **Galen of Pergamon** (129–199), **Franz Joseph Gall** (1758–1828), **Pierre Paul Broca** (1824–1880), **Gustav Theodor Fritsch** (1838–1927), **Eduard Hitzig** (1839–1907), **Wilder Graves Penfield** (1891–1976), **Herbert Henri Jasper** (1906–1999)

The ancient Greek physician Hippocrates was aware that the brain comprised the physical material underlying thoughts and emotions, and the Greek physician Galen declared, “Where the origin of the nerves is, there is the command of the soul.” However, it wasn’t until the 1800s that advanced research was performed with respect to cerebral localization—that is, the idea that different areas of the brain are specialized for different functions.

In 1796, German neuroanatomist Franz Joseph Gall conjectured that the brain should be considered as a mosaic of suborgans, each specialized to deal with various mental faculties, such as language, music, and so forth. However, he made the mistake of promoting the idea that the relative size and efficiency of these various suborgans could be inferred from the size of the overlying areas and bumps of the skull.

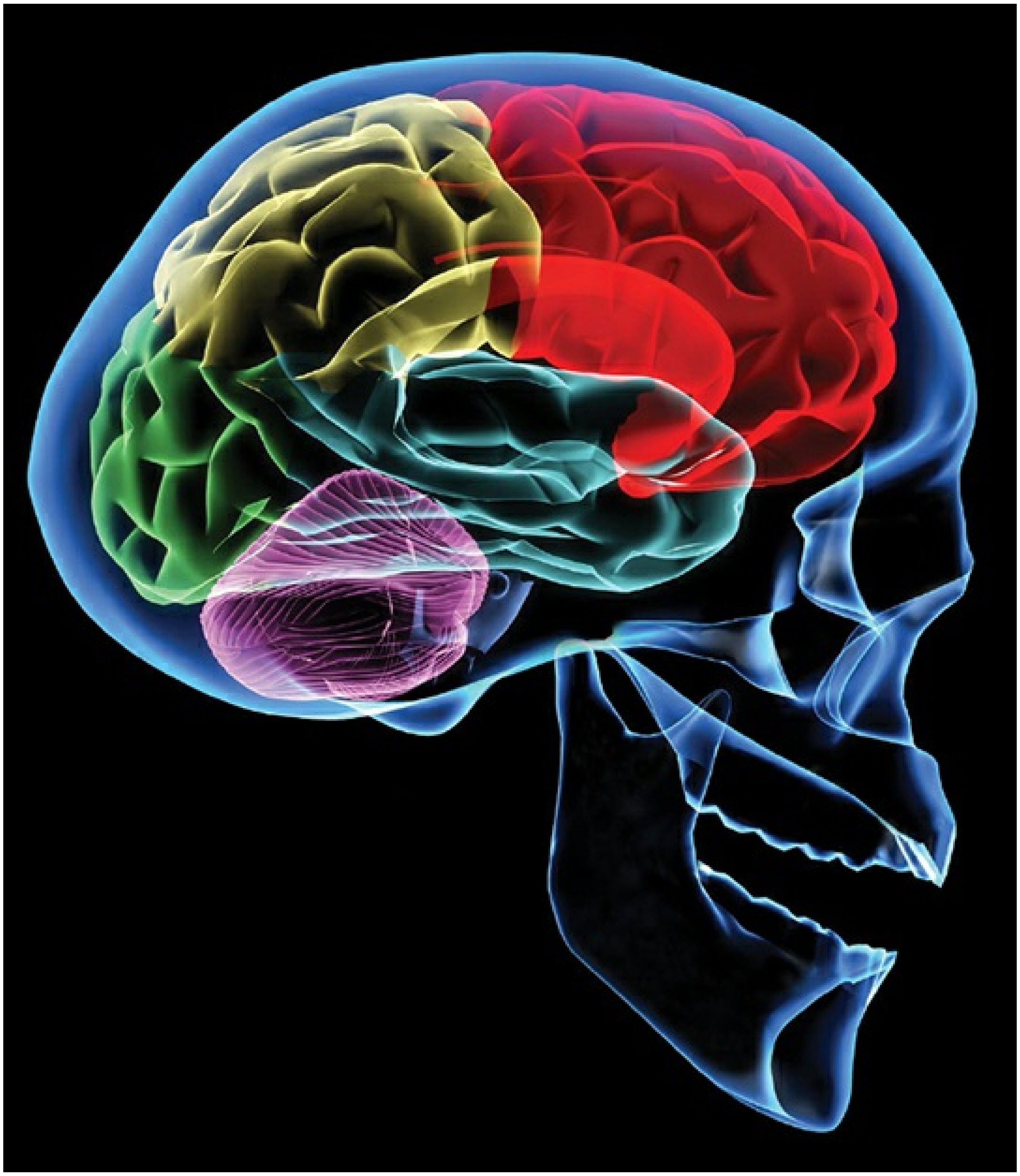
In 1861, French physician Pierre Broca discovered a particular region of the brain used for speech production. His findings were based on examination of two patients who had lost the ability to speak after injury to a particular region located on the frontal part of the left hemisphere of the brain, which today we refer to as Broca’s area. Interestingly, gradual destruction of

Broca’s area by, for example, a brain tumor can sometimes preserve significant speech functionality, which suggests that speech function can shift to nearby areas in the brain.

Additional important evidence for cerebral localization was provided around 1870 from German researchers Gustav Fritsch and Eduard Hitzig, whose experiments on dogs showed that local body movement could be elicited by electrical stimulation of specific brain areas. In the 1940s, Canadian researchers Wilder Penfield and Herbert Jasper continued investigations involving electrical stimulation of a brain hemisphere’s motor cortex, which produced contractions on the *opposite* side of the human body. They also created detailed functional maps of the brain’s motor areas (which control voluntary muscle movement) and sensory areas.

SEE ALSO Morgagni’s “Cries of Suffering Organs” (1761), Neuron Doctrine (1891), Brain Lateralization (1964).

The cerebral cortex includes the frontal lobe (red), parietal lobe (yellow), occipital lobe (green), and temporal lobe (blue-green). The frontal lobe is responsible for “executive functions” such as planning and abstract thinking. The cerebellum (purple) is the region at the bottom.



1861

Maxwell’s Equations • *Clifford A. Pickover*

James Clerk Maxwell (1831–1879)

“From a long view of the history of mankind,” writes physicist Richard Feynman, “seen from, say, ten thousand years from now—there can be no doubt that the most significant event of the 19th century will be judged as Maxwell’s discovery of the laws of electrodynamics. The American Civil War will pale into provincial insignificance in comparison with this important scientific event of the same decade.”

In general, Maxwell’s Equations are the set of four famous formulas that describe the behavior of the electric and magnetic fields. In particular, they express how electric charges produce electric fields and the fact that magnetic charges cannot exist. They also show how currents produce magnetic fields and how changing magnetic fields produce electric fields. If you let E represent the electric field, B represent the magnetic field, ε_0 represent the electric constant, μ_0 represent the magnetic constant, and J represent the current density, you can express Maxwell’s equations thus:

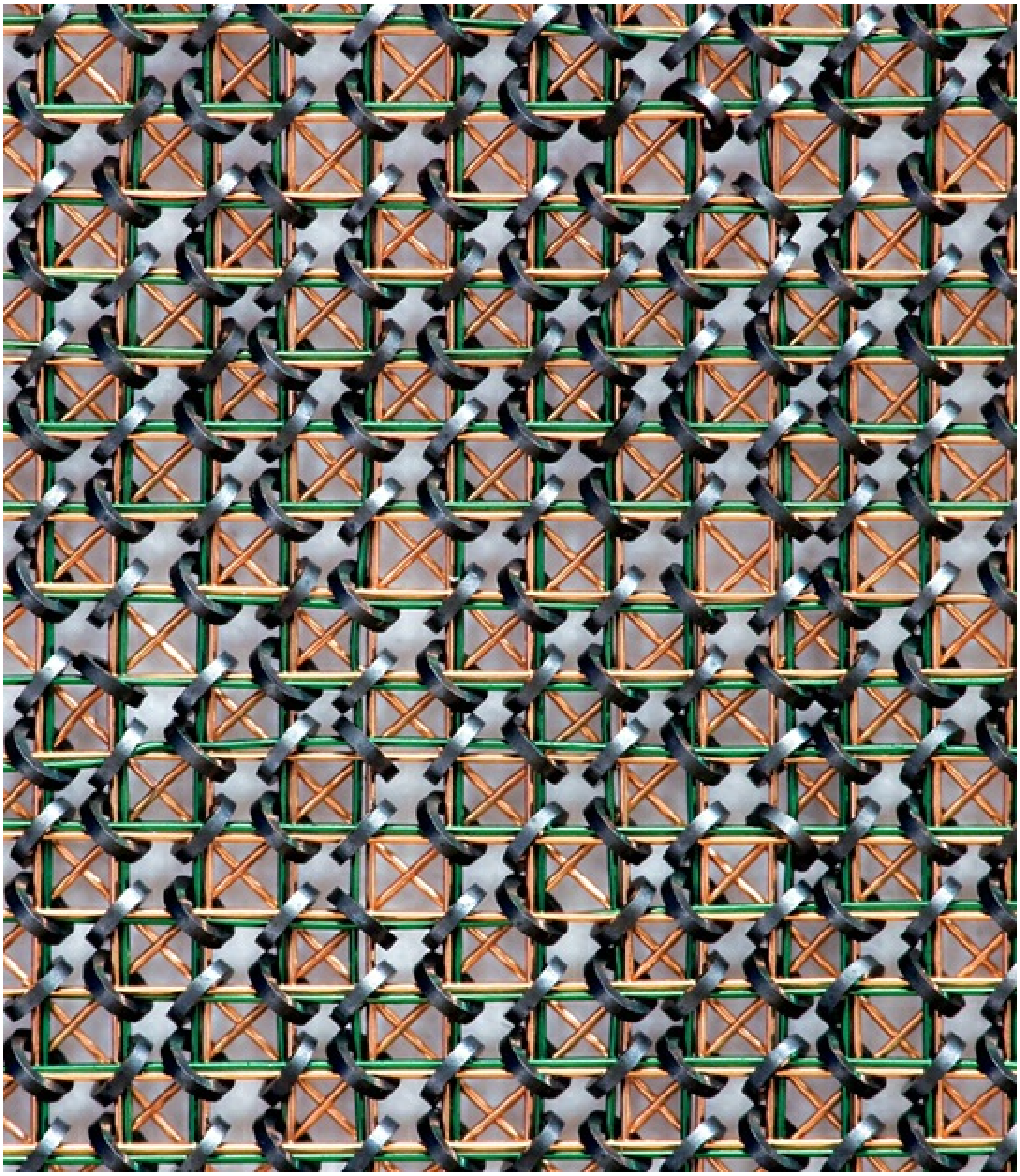
$\nabla \cdot E = \frac{\rho}{\varepsilon_0}$	Gauss' Law for Electricity
$\nabla \cdot B = 0$	Gauss' Law for Magnetism (no magnetic monopoles)
$\nabla \times E = -\frac{\partial B}{\partial t}$	Faraday's Law of Induction
$\nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}$	Ampère's Law with Maxwell's extension

Note the utter compactness of expression, which led Einstein to rate Maxwell's achievement on a par with that of Isaac Newton's. Moreover, the equations predicted the existence of electromagnetic waves.

Philosopher Robert P. Crease writes of the importance of Maxwell's equations: "Although Maxwell's equations are relatively simple, they daringly reorganize our perception of nature, unifying electricity and magnetism and linking geometry, topology and physics. They are essential to understanding the surrounding world. And as the first field equations, they not only showed scientists a new way of approaching physics but also took them on the first step towards a unification of the fundamental forces of nature."

SEE ALSO Ampère's Law of Electromagnetism (1825), Faraday's Laws of Induction (1831), Theory of Everything (1984).

LEFT: *Mr. and Mrs. James Clerk Maxwell, 1869.* RIGHT: *Computer core memory of the 1960s can be partly understood using Ampere's Law in Maxwell's Equations, which describes how a current-carrying wire produces a magnetic field that circles the wire and, thus, can cause the core (doughnut shape) to change its magnetic polarity.*



1862

Germ Theory of Disease • *Clifford A. Pickover*

Marcus Terentius Varro (116 BCE–27 BCE), **Louis Pasteur** (1822–1895)

To our modern minds, it is obvious that germs cause disease. We chlorinate our drinking water, use antibiotic ointments, and hope our doctors wash their hands. We are fortunate that the French chemist and microbiologist Louis Pasteur conducted his pioneering research into the causes and preventions of disease—and for experiments that supported the germ theory of disease, which suggests that microorganisms are the cause of many diseases.

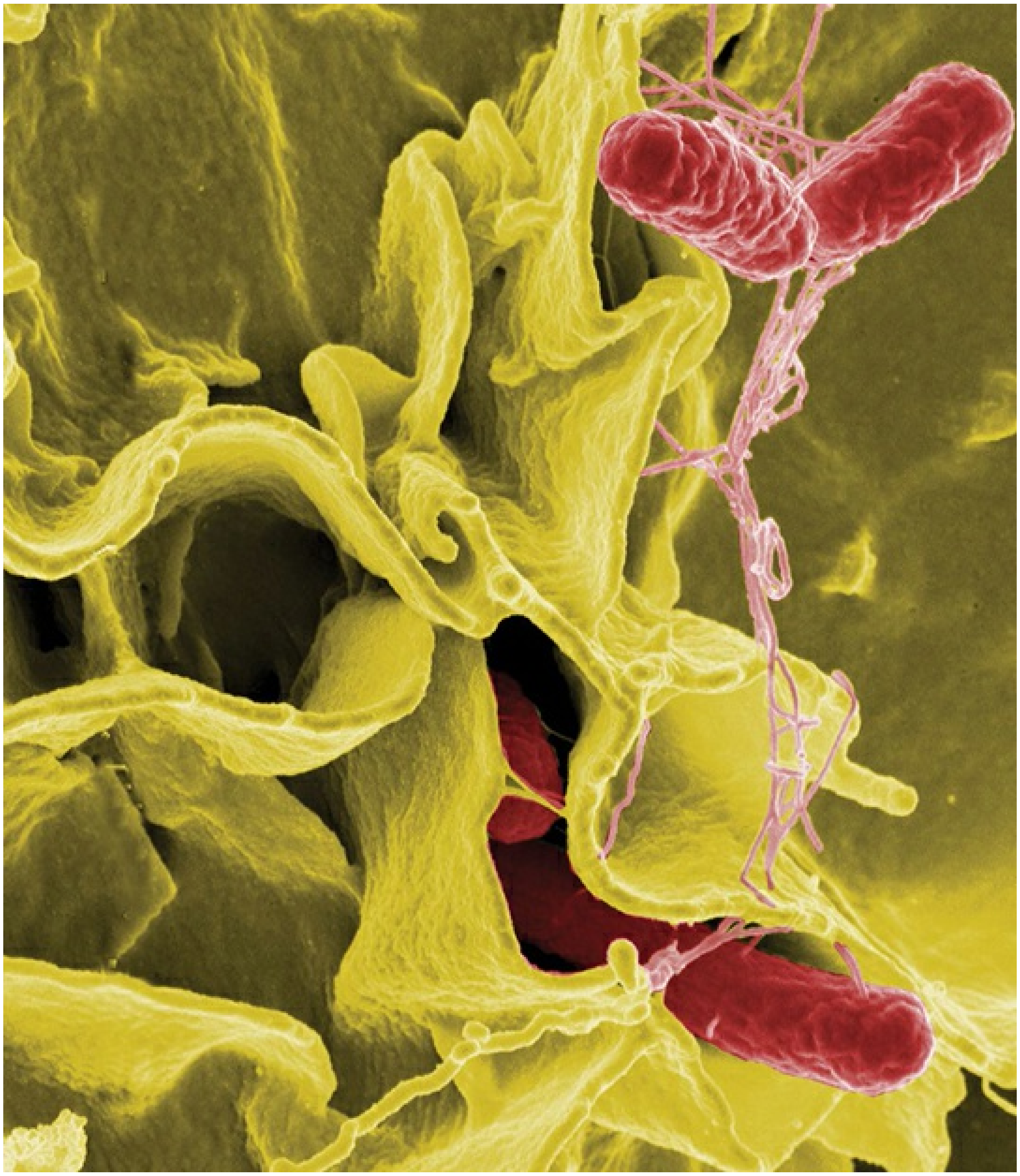
In one famous experiment, conducted in 1862, Pasteur demonstrated that the growth of bacteria in sterilized nutrient broths is not due to spontaneous generation—a theory that suggests that life often arises from inanimate matter. For example, no organisms grew in flasks that contained a long, thin, twisting neck that made it extremely unlikely for dust, spores, and other particles to enter the broth. Only when Pasteur's flasks were broken open did organisms begin to grow in the medium. If spontaneous generation were valid, the broth in the curved-neck flasks would have eventually become infected because the germs would have spontaneously generated.

During his career, Pasteur studied fermentation in wines and diseases in sheep and silkworms. He created a vaccination for rabies. He showed that pasteurization (heating of a beverage to a specific temperature for a period of time) diminished microbial growth in food. In his studies of anthrax, he showed that even extremely diluted solutions of bacteria from infected animal blood could kill animals if the bacteria were allowed to multiply in the culture medium before injection into animals.

Pasteur was far from the first individual to suggest that invisible creatures caused diseases. Even the Roman scholar Marcus Terentius Varro published in 36 BCE a warning for people living too close to swamps, "because there are bred certain minute creatures which cannot be seen by the eyes, which float in the air and enter the body through the mouth and nose and there cause serious diseases." However, the breadth of Pasteur's scientific experiments into microbial causes of disease revolutionized medicine and public health.

SEE ALSO *Micrographia* (1665), Semmelweis's Hand Washing (1847), Cell Division (1855), Antiseptics (1865), Chlorination of Water (1910).

Color-enhanced scanning electron micrograph showing Salmonella typhimurium (red) invading cultured human cells (courtesy of Rocky Mountain Laboratories, NIAID, and NIH). Salmonella causes illnesses such as typhoid fever and food-borne illnesses.



1864

Electromagnetic Spectrum • *Clifford A. Pickover*

Frederick William Herschel (1738–1822), **Johann Wilhelm Ritter** (1776–1810), **James Clerk Maxwell** (1831–1879), **Heinrich Rudolf Hertz** (1857–1894)

The electromagnetic spectrum refers to the vast range of frequencies of electromagnetic (EM) radiation. It is composed of waves of energy that can propagate through a vacuum and that contain electric and magnetic field components that oscillate perpendicular to each other. Different portions of the spectrum are identified according to the frequency of the waves. In order of increasing frequency (and decreasing wavelength), we have radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays.

We can see light with wavelengths between 4,000 and 7,000 angstroms, where an angstrom is equal to 10^{-10} meters. Radio waves may be generated by electrons that move back and forth in transmission towers and have wavelengths ranging from several feet to many miles. If we represent the electromagnetic spectrum as a 30-octave piano, in which the wavelength of radiation doubles with each octave, visible light occupies only part of an octave. If we wanted to represent the entire spectrum of radiation that has been detected by our instruments, we would need to add at least 20 octaves to the piano.

Extraterrestrials may have senses beyond our own. Even on the Earth, we find examples of creatures with increased sensitivities. For example, rattlesnakes have infrared detectors that give them “heat pictures” of their surroundings. To our eyes, both the male and female Indian luna moths are light green and indistinguishable from each other, but the luna moths themselves perceive the ultraviolet range of light. Therefore, to them, the female looks quite different from the male. Other creatures have difficulty seeing the moths when they rest on green leaves, but luna moths are not camouflaged to one another; rather, they see each other as brilliantly colored. Bees can also detect ultraviolet light. In fact, many flowers have beautiful patterns that bees can see to guide them to the flower. These attractive and intricate patterns are totally hidden from human perception.

The physicists listed at the top of this entry played key research roles with respect to the electromagnetic spectrum.

SEE ALSO Newton's Prism (1672), Wave Nature of Light (1801), X-rays (1895), Cosmic Microwave Background (1965).

To our eyes, male and female luna moths are light green and indistinguishable from each other. But the luna moths themselves perceive in the ultraviolet range of light, and to them the female looks quite different from the male.

1865

Antiseptics • *Clifford A. Pickover*

William Henry (1775–1836), **Ignaz Philipp Semmelweis** (1818–1865), **Louis Pasteur** (1822–1895), **Joseph Lister** (1827–1912), **William Stewart Halsted** (1852–1922)

In 1907, the American physician Franklin C. Clark wrote, “Three notable events characterize the history of medicine, each of which in turn has completely revolutionized the practice of surgery.” The first event involved the use of ligatures to stem the flow of blood during surgeries—for example, as performed by the French surgeon Ambroise Paré. The second involved methods for decreasing pain through general anesthetics such as ether, attributed to several Americans. The third concerned antiseptic surgery, which was promoted by British surgeon Joseph Lister. Lister’s use of carbolic acid (now called phenol) as a means for sterilizing wounds and surgical instruments dramatically reduced postoperative infections.

Louis Pasteur’s work on the germ theory of disease provided a stimulus for Lister to use carbolic acid in an attempt to destroy microorganisms. In 1865, he successfully treated a compound fracture of the leg, in which the bone juts through the skin, by dressing the leg with cloths dipped in carbolic acid solutions. Lister published his findings in the paper “Antiseptic Principle of the Practice of Surgery” in 1867.

Lister was not the first to suggest various forms of sterilization. For example, the British chemist William Henry advised sterilization of clothing through heating, and Hungarian obstetrician Ignaz Semmelweis advocated hand washing to prevent the spread of disease by physicians. Nevertheless, Lister’s slopping of carbolic acid onto open wounds usually prevented the development of the horrific infections that so often occurred in hospitals of his time. His writings and talks convinced medical professionals of the need for using antiseptics.

Antiseptics are usually applied directly to the body surface. Modern methods for preventing infections focus more on the use of aseptic methods that involve sterilization to remove bacteria *before* they come near a patient (e.g., disinfection of equipment and the use of surgeons' masks). Antibiotic drugs are also used today to fight internal infections. In 1891, William Halsted pioneered the use of rubber gloves in surgery.

SEE ALSO Semmelweis's Hand Washing (1847), Germ Theory of Disease (1862), Chlorination of Water (1910), Penicillin (1928).

Manuka honey has been shown to have antibacterial properties that assist in wound healing. Such honey is made by bees in New Zealand that feed on the manuka bush, Leptospermum scoparium.

1865

Mendel's Genetics • *Clifford A. Pickover*

Gregor Johann Mendel (1822–1884)

The Austrian priest Gregor Mendel studied the inheritance of easily identifiable traits in pea plants, such as color or wrinkling, and showed that the inheritance could be understood in terms of mathematical laws and ratios. Although his work was not recognized in his lifetime, the laws that he discovered formed the foundation of genetics—the science of heredity and variation in organisms.

In 1865, Mendel reported on his studies of more than 20,000 pea plants, conducted over six years, which led him to formulate his laws of genetics. He observed that organisms inherit traits via discrete units that we now refer to as genes. This finding was in contrast to other popular theories of his time, such as an individual inheriting a smooth blend of traits from the parents, or an individual inheriting "acquired characteristics" from their parents (such as a son having large muscles simply because his father lifted weights).

As an example, consider that in peas, each plant has two alleles (versions) of each gene, and that the offspring inherit one allele from each parent. It is a matter of chance which gene from each parent is received. If the offspring receives a gene for a yellow seed together with a gene for a green seed, the yellow gene may dominate in the offspring, but the gene for green is still present and is transmitted to the plant's descendants in a consistent and predictable manner.

Today, medical geneticists aim to understand how genetic variations play a role in human health and disease. For example, the disease cystic fibrosis, which includes difficulty breathing among other symptoms, is caused by a mutation (change) in a single gene that affects membranes of cells. The ideas associated with Mendel's genetics eventually led to a better understanding of genes and chromosomes (composed of a DNA molecule containing many genes), along with the potential to cure many diseases and shape the evolution of the human species. Human genes have even been placed into bacteria to create large quantities of insulin for diabetic individuals.

SEE ALSO Chromosomal Theory of Inheritance (1902), Epigenetics (1983), Human Genome Project (2003), Gene Therapy (2016).

Gregor Mendel studied the inheritance of easily identifiable traits in pea plants, such as color or wrinkling, and showed that inheritance could be understood in terms of simple mathematical ratios.

1869

Periodic Table • *Derek B. Lowe*

Lothar Meyer (1830–1895), **Dmitri Ivanovich Mendeleev** (1834–1907), **John Alexander Reina Newlands** (1837–1898), **Antonius van den Broek** (1870–1926), **Henry Gwyn Jeffreys Moseley** (1887–1915)

The periodic table is the undisputed centerpiece of chemistry. Built into its arrangement is a wealth of hard-earned knowledge about atomic structure, reactivity, bonding, and other crucial concepts. The building blocks of our world are all there, organized in a way that shows their deepest relations.

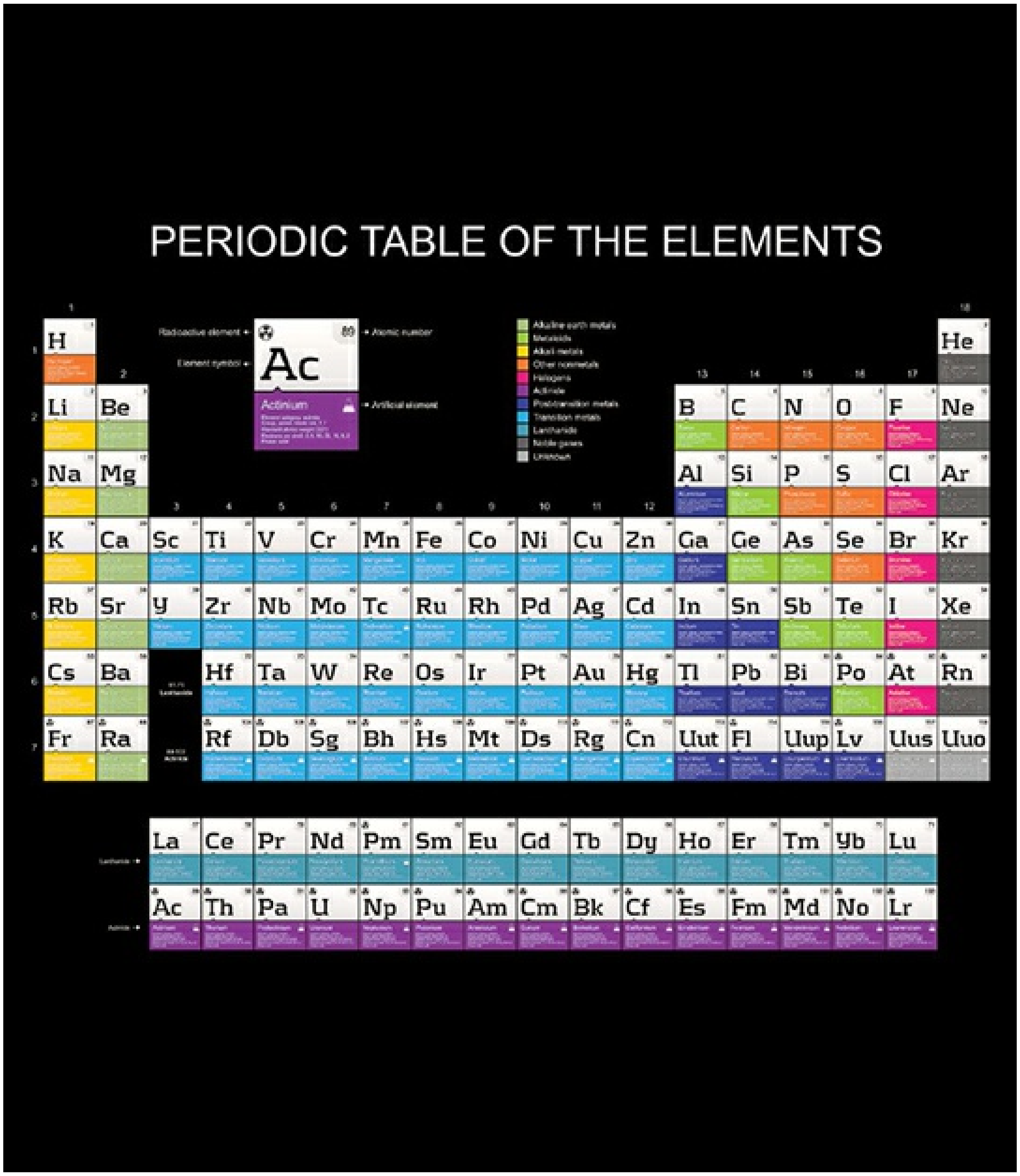
German chemist Lothar Meyer and English chemist John Alexander Reina Newlands were two of the first to realize (independently) that arranging the known elements by their atomic weights revealed underlying patterns. Elements with similar behavior tended to cluster together (such as sodium and potassium, both soft, highly reactive metals). In Russia, chemist Dmitri Ivanovich Mendeleev, unaware of the work of Meyer and Newlands, was thinking along the same lines, and in 1869 he presented his own arrangement based on atomic weights and the number of bonds the various elements tended to form. It not only had all the known elements, but it also boldly included gaps where new ones were predicted to exist. Their discovery (and the successful prediction of their properties) was powerful evidence that Mendeleev had it right.

Modern tables are ordered by increasing atomic number (the number of protons in the nucleus), as suggested by Dutch physicist Antonius van den Broek and by the work of English physicist Henry Gwyn Jeffreys Moseley. The columns (called *groups*) represent increasing numbers of electrons in each atom’s outermost “shell” (called an *orbital*), from just one electron on the far left column (reactive sodium and its alkali metal group members) over to the unreactive noble gases on the far right, with their perfectly filled orbitals. Then a new row (called a period) starts, with a heavier alkali metal on one end, going all the way over to a heavier noble gas. The heavier elements demonstrate the greater number of electrons that go into the outer orbitals, and the table spreads out accordingly.

It’s no exaggeration to say that many of the chemistry advances over thousands of years were leading up to this: Understanding how the elements differ and why has been one of the great works of the human race.

SEE ALSO Electron (1897), Atomic Nucleus (1911), Hydrogen Bonding (1920).

The current periodic table, where all of chemistry begins.


PERIODIC TABLE OF THE ELEMENTS
Radioactive element
Element symbol
Ac
89
Atomic number
Actinium
Artificial element
Alkaline earth metals
Metalloids
Alkali metals
Other nonmetals
Halogens
Actinide
Post-transition metals
Transition metals
Lanthanide
Noble gases
Unknown
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Rf Db Sg Bh Hs Mt Ds Rg Cn Uut Fl Uup Lv Uus Uuo
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr

1874

Cantor’s Transfinite Numbers • *Clifford A. Pickover*

Georg Cantor (1845–1918)

German mathematician Georg Cantor founded modern set theory and introduced the mind-boggling concept of transfinite numbers that can be used to denote the relative “sizes” of an infinite collection of objects. The smallest transfinite number is called *aleph-nought*, written as $\aleph_0$, which counts the number of integers. If the number of integers is infinite (with $\aleph_0$ members), are there yet higher levels of infinity? It turns out that even though there are an infinite number of integers, rational numbers (numbers that can be expressed as fractions), and irrational numbers (like the square root of 2 that cannot be expressed as a fraction), the infinite number of irrationals is in some sense greater than the infinite number of rationals or integers. Similarly, there are more *real* numbers (which include rational and irrational numbers) than there are integers.

Cantor’s shocking concepts about infinity drew widespread criticism—which likely contributed to Cantor’s bouts of severe depression and multiple institutionalizations—before being accepted as a fundamental theory. Cantor also equated his concept of the Absolute Infinite, which transcended the transfinite numbers, with God. He wrote, “I entertain no doubts as to the truths of the transfinites, which I recognized with God’s help and which, in their diversity, I have studied for more than twenty years.” In 1884, Cantor wrote to Swedish mathematician Gösta Mittag-Leffler explaining that he was not the creator of his new work, but merely a reporter. God had provided the inspiration, leaving Cantor only responsible for the organization and style of his papers. Cantor said that he knew that transfinites were real because “God had told me so,” and it would have diminished God’s power had God only created *finite* numbers. Mathematician David Hilbert described Cantor’s work as “the finest product of mathematical genius and one of the supreme achievements of purely intellectual human activity.”

SEE ALSO Sieve of Eratosthenes (c. 240 BCE) Transcendental Numbers (1844), Gödel’s Theorem (1931).

Photo of Georg Cantor and his wife, taken around 1880. Cantor’s startling ideas about infinity initially drew widespread criticism, which may have exacerbated his severe and chronic battles with depression.

1875

Boltzmann’s Entropy Equation • *Clifford A. Pickover*

Ludwig Eduard Boltzmann (1844–1906)

“One drop of ink may make a million think,” says an old proverb. Austrian physicist Ludwig Boltzmann was fascinated by statistical thermodynamics, which focuses on the mathematical properties of large numbers of particles in a system, including ink molecules in water. In 1875, he formulated a mathematical relationship between entropy S (roughly, the disorder of a system) and the number of possible states of the system W in a compact expression: $S = k \cdot \log W$. Here, k is Boltzmann’s constant.

Consider a drop of ink in water. According to Kinetic Theory, the molecules are in constant random motion and always rearranging themselves. We assume that all possible arrangements are equally probable. Because most of the arrangements of ink molecules do not correspond to a drop of clustered ink molecules, most of the time we will not observe a drop. Mixing occurs spontaneously simply because so many more arrangements exist that are mixed than that are not. A spontaneous process occurs because it produces the most probable final state. Using the formula $S = k \cdot \log W$, we can calculate the entropy and can understand why the more states that exist, the greater the entropy. A state with a high probability (e.g. a mixed ink state) has a large value for the entropy, and a spontaneous process produces the final state of greatest entropy, which is another way of stating the Second Law of Thermodynamics. Using the terminology of thermodynamics, we can say that there are a number of ways W (number of *microstates*) that exist to create a particular *macrostate*—in our case, a mixed state of ink in a glass of water.

Although Boltzmann's idea of deriving thermodynamics by visualizing molecules in a system seems obvious to us today, many physicists of his time criticized the concept of atoms. Repeated clashes with other physicists, combined with an apparent lifelong struggle with bipolar disorder, may have contributed to the physicist's suicide in 1906 while on vacation with his wife and daughter. His famous entropy equation is engraved on his tombstone in Vienna.

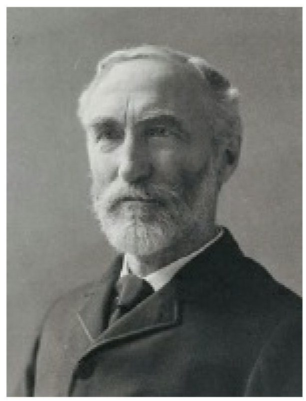
SEE ALSO Brownian Motion (1827), Second Law of Thermodynamics (1850), Kinetic Theory (1859).

LEFT: *Ludwig Eduard Boltzmann.* RIGHT: *Imagine that all possible arrangements of ink and water molecules are equally probable. Because most of the arrangements do not correspond to a drop of clustered ink molecules, most of the time we will not observe a droplet once the ink drop is added.*

1876

Gibbs Free Energy • *Derek B. Lowe*

Josiah Willard Gibbs (1839–1903)



If you want to look under the hood of chemistry and see what really makes things work, study thermodynamics. It measures changes in energy, the driving force for all chemical processes. Credit here goes to American scientist Josiah Willard Gibbs, whose theoretical insights and great mathematical ability turned thermodynamics into a precise scientific tool with applications in every possible area of chemistry, physics, and biology.

In 1876, he published his work on chemical systems and the "free energy" of reactions (now called *Gibbs free energy*, or *G*, in his honor). When a system changes from one state into another (chemically, as in a reaction, or physically, as in melting or boiling), the change in G (called Δ*G* or *delta*-*G*) is the work exchanged by the system with its surroundings (for example, the heat that is given off). Chemical reactions that can spontaneously give off energy show a negative ΔG. A fire is a perfect example. Reactions that have even larger negative ΔG values (such as the thermite reaction or the decomposition of nitroglycerine) can be dangerously energetic. In contrast, reactions with a positive ΔG—photosynthesis in plants, for example—require the addition of external energy, such as sunlight.

The other key thing to know about ΔG is that it's made up of two parts: enthalpy and entropy. Enthalpy (designated by the letter *H*) can be thought of as a pure measure of heat and energy, while entropy (*S*) is related to disorder and the reactants' "degrees of freedom" (i.e., how many different ways that they can move and vibrate). Chemists think in these terms constantly, gaining great insight into reactions by keeping all these factors in mind.

Some chemical reactions are spontaneous even though they actually get cold and soak up heat from their surroundings, like an instant "cold pack." This can happen because the entropy of the final state is so much higher (ΔS) than that of the starting materials, canceling out an unfavorable enthalpy change (ΔH), and giving an overall favorable ΔG. If both ΔH and ΔS are large and negative, though, you have an explosion in the making!

SEE ALSO Conservation of Energy (1843), Second Law of Thermodynamics (1850), Boltzmann's Entropy Equation (1875).

LEFT: *Josiah Willard Gibbs, 1903.* RIGHT: *This explosive thermite reaction has a large negative ΔG value.*

1876

Telephone • *Marshall Brain*

Alexander Graham Bell (1847–1922)

Imagine that the year is 1850 and you want to talk to someone. You have exactly one option: You can travel and meet with that person face-to-face, which could take days or weeks, depending on distance. Your alternative: a handwritten letter. Or, by 1850, the telegraph system has started to expand. But the simple act of talking to someone still requires a face-to-face meeting.

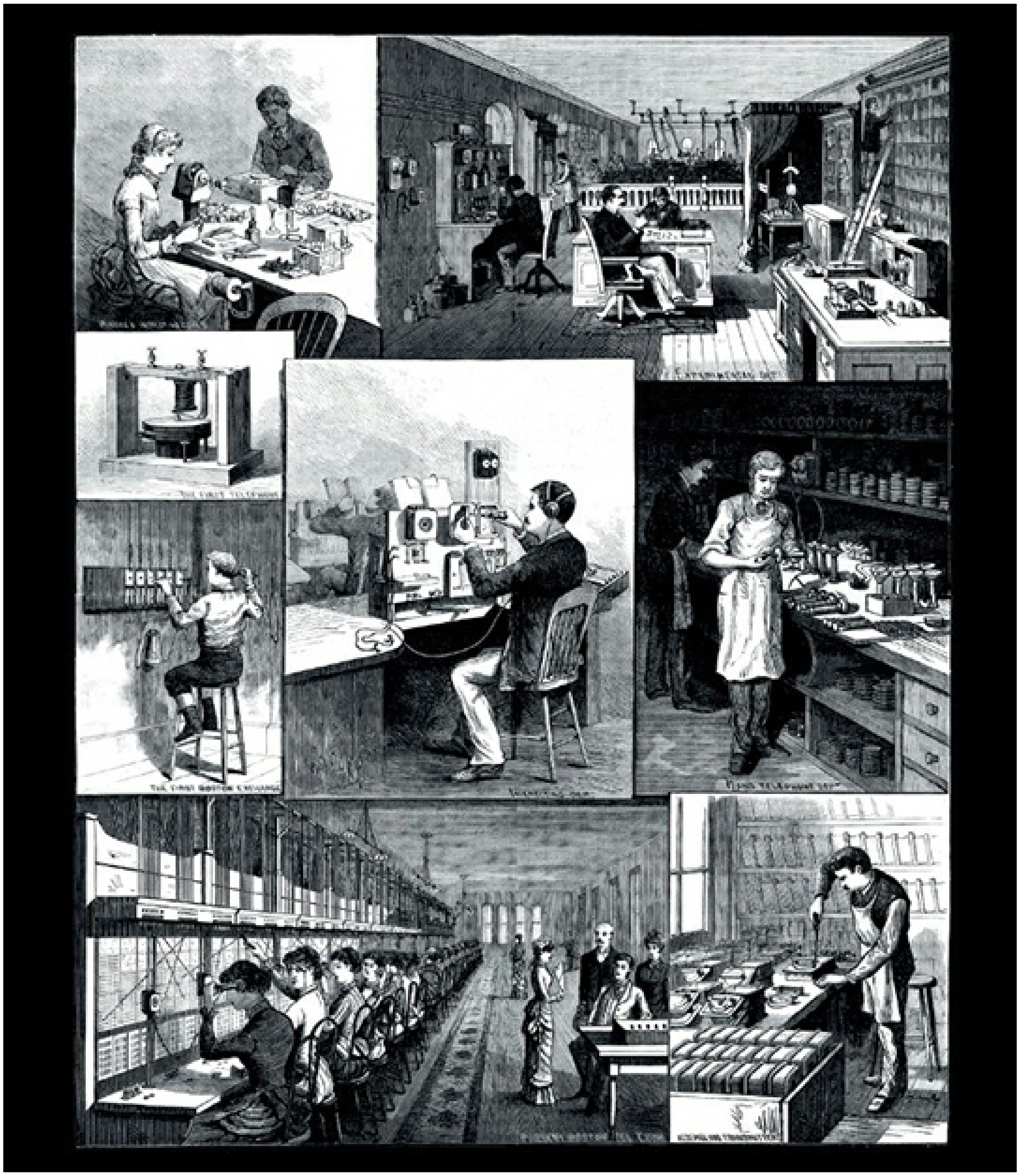
Enter the telephone. The patent for Alexander Graham Bell's telephone was issued in 1876. The device itself was incredibly simple—a microphone made of carbon granules and a speaker. To connect two telephones together, all you needed was copper wire and a small source of electric current, like a battery—with this innovation, two people talked to each other at a distance for the first time.

How did engineers scale this up? The first innovation was the central office. In a town, copper wires ran from each home or business to the central office. An operator could connect any line to any other line in town. Wires are added to connect the town to the next town over. At that point, anyone in the two towns could communicate. As additional towns connected, this led to the creation of regional central offices. Eventually trunk lines spanned the country, then the world, and now everyone could connect to everyone else.

Engineers developed mechanical switches to replace the human operators. The telephone dial told the switches what to do. As a result, the cost of calling fell. Engineers created much smaller computers to replace the mechanical switches, and touch-tone dialing became possible. The cost of calling fell again. Engineers turned voice signals into digital bits and sent the bits through fiber optic cables, drastically reducing costs and increasing capacity. Then engineers created voice over IP (VoIP) so calls were routed through the Internet. Internet telephony was born and calling became free on many VoIP networks. The success story for engineering: taking something that used to be impossible and eventually making it free!

SEE ALSO Telegraph System (1837), Fiber Optics (1841), Radio Station (1920), ARPANET (1969).

Bell Telephone Company, America. Engraving from Scientific American, 1884.



1878

Enzymes • *Michael C. Gerald with Gloria E. Gerald*

Wilhelm Kühne (1837–1900), **Eduard Buchner** (1860–1917), **James B. Summer** (1887–1955)

Life cannot exist without enzymes. Thousands of chemical reactions occur in living cells: old cells are being replaced by new ones; simple molecules link to form complex ones; food is digested and converted to energy; waste materials are disposed of; and cells reproduce. These reactions, involving buildup and breakdown, are collectively referred to as metabolism. For each of these reactions to occur, a certain degree of energy is required (activation energy) and in the absence of such energy, these reactions would not occur spontaneously. The presence of these enzymes—which are usually proteins or RNA enzymes—reduces the amount of activation energy required for these reactions to occur and increases the rate of these reactions by millions. In the process, enzymes are neither consumed nor chemically changed.

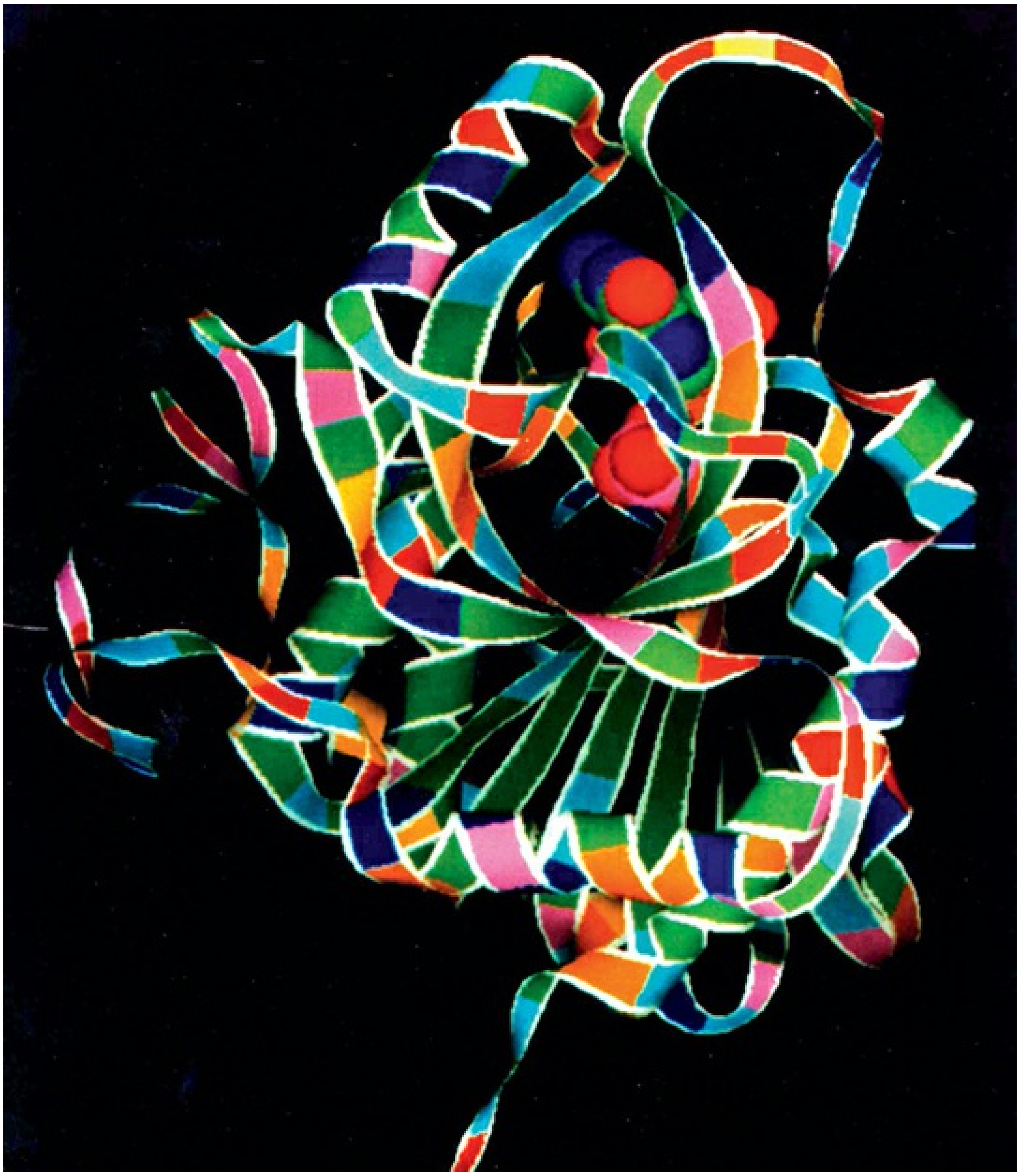
Each of the chemical reactions in the body is a component of a pathway or cycle, and most enzymes are highly specific and act on only a single substrate (reactant) in the pathway to produce a product in the metabolic sequence. Most of the more than 4,000 enzymes in living cells are proteins, with a unique three-dimensional configuration, the shape of which accounts for their specificity. An enzyme is commonly named by adding the suffix *ase* to the root name of the substrate on which it acts, although more specific (and descriptive) names are used in chemically oriented literature.

It was known in the late seventeenth and early eighteenth centuries that meat was digested by secretions in the stomach and starch could be broken down to simple sugars by saliva and plant extracts. Wilhelm Kühne, a

German physiologist, was the first to coin the name *enzyme* in 1878 to refer to trypsin, a protein-digesting enzyme he had discovered, and, in 1897, Eduard Buchner at the University of Berlin first demonstrated that enzymes could function outside living cells. In 1926, working with the jack bean, James Summer at Cornell University isolated and crystallized the first enzyme, urease, and provided conclusive proof that it was a protein. Summer was the co-recipient of the 1946 Nobel Prize in Chemistry.

SEE ALSO Cellular Respiration (1937), Ribosomes (1955), Polymerase Chain Reaction (1983).

Certain anticancer and immunosuppressive drugs target purine nucleoside phosphorylase (PNP), an enzyme that carries out housekeeping functions by clearing away certain waste molecules that are formed when DNA is broken down. The image depicts a computer-generated model of PNP.



1878

Incandescent Light Bulb • *Clifford A. Pickover*

Joseph Wilson Swan (1828–1914), **Thomas Alva Edison** (1847–1931)

The American inventor Thomas Edison, best known for his development of the light bulb, once wrote, "To invent you need a good imagination and a pile of junk." Edison was not the only person to have invented a version of the *incandescent* light bulb—that is, a light source that makes use of heat-driven light emissions. Other equally notable inventors include Joseph Swan of England. However Edison is best remembered because of the combination of factors he helped to promote—a long-lasting filament, the use of a higher vacuum within the bulb than others were able to produce, and a power distribution system that would make the light bulb of practical value in buildings, streets, and communities.

In an incandescent light bulb, an electric current passes through the filament, heating it to produce light. A glass enclosure prevents oxygen in the air from oxidizing and destroying the hot filament. One of the greatest challenges was to find the most effective material for the filament. Edison's carbonized filament of bamboo could emit light for more than 1,200 hours. Today, a filament made of tungsten wire is often used, and the bulb is filled with an inert gas such as argon to reduce evaporation of material from the filament. Coiled wires increase the efficiency, and the filament within a typical 60-watt, 120-volt bulb is actually 22.8 inches (580 millimeters) in length.

If a bulb is operated at low voltages, it can be surprisingly long lasting. For example, the “Centennial Light” in a California fire station has been burning almost continually since 1901. Generally, incandescent lights are inefficient in the sense that about 90% of the power consumed is converted to heat rather than visible light. Although today more efficient forms of light bulbs (e.g. compact fluorescent lamps) are starting to replace the incandescent light bulbs, the simple incandescent bulb once replaced the soot-producing and more dangerous lamps and candles, changing the world forever.

SEE ALSO Wave Nature of Light (1801), Fiber Optics (1841), Electromagnetic Spectrum (1864).

Edison light bulb with a looping carbon filament.

1878

Power Grid • *Marshall Brain*

In 1878, at the Paris World's Fair, visitors marveled at the Yablochov arc lamps (patented by Pavel Yablochov in 1876) powered by Zénobe Gramme dynamos. This was an example of an early commercial system of high-voltage power—the kind of power grid that exists invisibly behind the scenes around the world today.

It is possible to imagine a society where there is no power grid—where every home and business generates its own power on-site. But this approach has efficiency problems. A big power plant can realize economies of scale when purchasing fuel and can apply significant resources to emission controls. Advanced technologies like nuclear power are not possible without a big power plant. And site-specific power sources like hydropower, solar power, and wind turbines only really make sense if there is a grid. A power grid can also improve reliability. When a big power plant needs to go offline for maintenance, other power plants in the area use the grid to make up the load.

It is amazing to realize that the power grid has only two key components: wire and transformers. Transformers can multiply voltages up and down. For long distance transmission, transformers boost the voltage to 700,000 volts or more. Once the power arrives at its destination, transformers step down the voltage. It might travel at 40,000 volts in a community, and then 3,000 volts in a neighborhood. At your house, a final transformer brings it to 240 and 120 volts for use in your wall outlets and light switches.

The grid is not perfect, and occasionally we see widespread blackouts. On a sweltering summer day with the whole grid running at peak loading, a failure in a key transmission line can cause an irresolvable problem. Other lines try to pick up the load from the failed line, but they overload and fail. A ripple effect can leave several states in the dark. Engineers are working on new architectures to prevent this problem as well. Once perfected, the grid will be even more invisible.

SEE ALSO Von Guericke's Electrostatic Generator (1660), Coulomb's Law of Electrostatics (1785), Battery (1800), Electron (1897).

A transmission tower often makes use of a steel lattice that supports an overhead power line. Without a power grid, energy would have to be generated on site.

1887

Michelson-Morley Experiment • *Clifford A. Pickover*

Albert Abraham Michelson (1852–1931) and **Edward Williams Morley** (1838–1923)

"It is hard to imagine nothing," physicist James Trefil writes. "The human mind seems to want to fill empty space with some kind of material, and for most of history that material was called the aether. The idea was that the emptiness between celestial objects was filled with a kind of tenuous Jell-O."

In 1887, physicists Albert Michelson and Edward Morley conducted pioneering experiments in order to detect the luminiferous aether thought to be pervading space. The aether idea was not too crazy—after all, water waves travel through water and sound travels through air. Didn't light also require a medium through which to propagate, even in an apparent vacuum? In order to detect aether, the researchers split a light beam into two beams that traveled at right angles to each other. Both beams were reflected back and recombined to produce a striped interference pattern that depended on the time spent traveling in both directions. If the Earth moved through an aether, this should be detectable as a change in the interference pattern produced when one of the light beams (which had to travel *into* the aether "wind") was slowed relative to the other beam. Michelson explained the idea to his daughter, "Two beams of light race against each other, like two swimmers, one struggling upstream and back, while the other, covering the same distance just crosses and returns. The second swimmer will always win if there is any *current* in the river."

In order to make such fine measurements, vibrations were minimized by floating the apparatus on a pool of mercury, and the apparatus could be rotated relative to the motion of the Earth. No significant change in the interference patterns was found, suggesting that the Earth did not move through an “aether wind”—making the experiment the most famous “failed” experiment in physics. This finding helped to persuade other physicists to accept Einstein’s Special Theory of Relativity.

SEE ALSO Wave Nature of Light (1801), Electromagnetic Spectrum (1864), Special Theory of Relativity (1905).

The Michelson-Morley Experiment demonstrated that the earth did not move through an aether wind. In the late 1800s, a luminiferous aether (the light-bearing substance artistically depicted here) was thought to be a medium for the propagation of light.

1888

Tesseract • *Clifford A. Pickover*

Charles Howard Hinton (1853–1907)

I know of no subject in mathematics that has intrigued both children and adults as much as the idea of a fourth dimension, a spatial direction different from all the directions of our everyday three-dimensional space. Theologians have speculated that the afterlife, heaven, hell, angels, and our souls could reside in a fourth dimension. Mathematicians and physicists frequently use the fourth dimension in their calculations. It’s part of important theories that describe the very fabric of our universe.

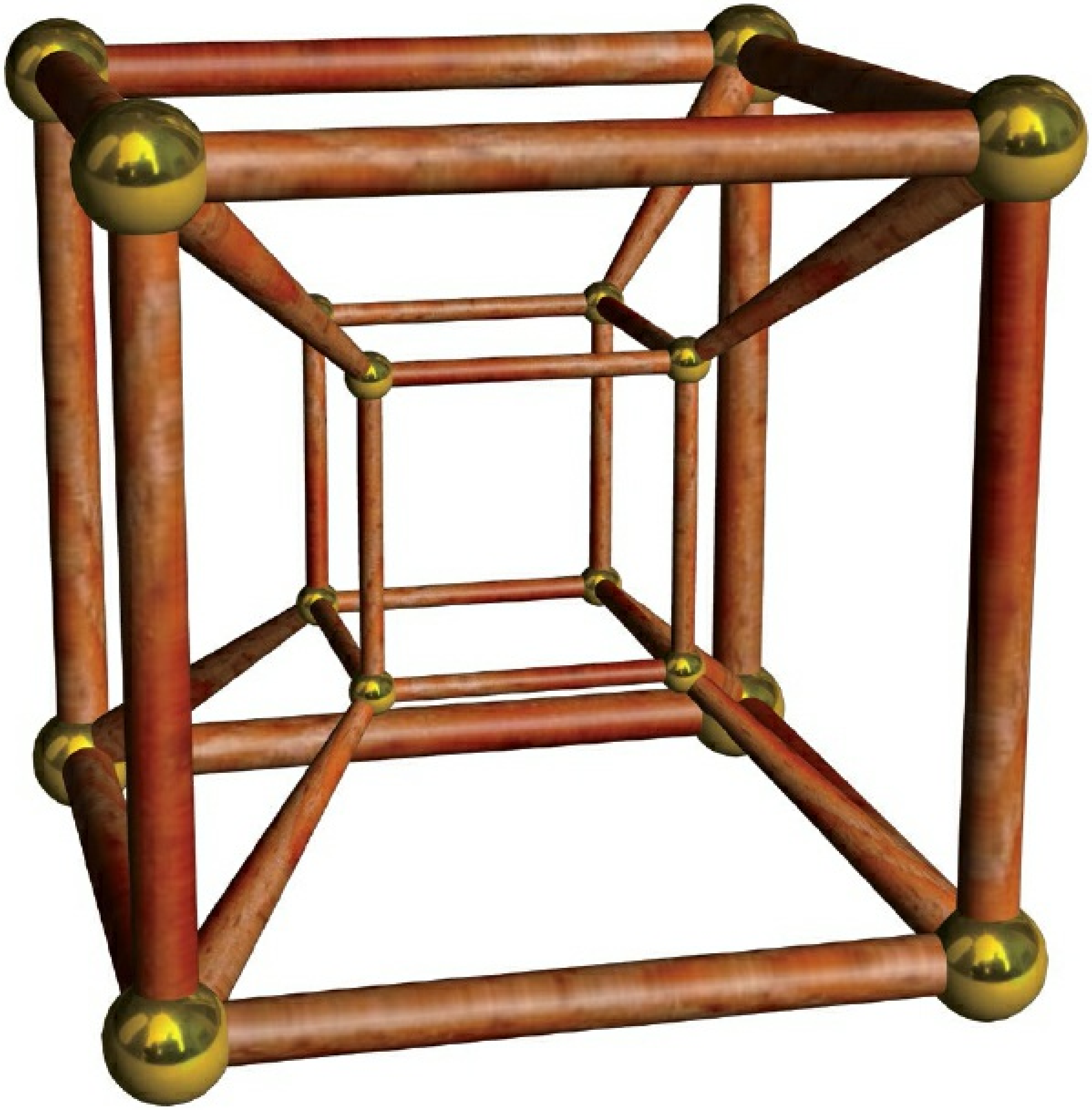
The tesseract is the four-dimensional analog of the ordinary cube. The term *hypercube* is used more generally when referring to cube analogues in other dimensions. Just as a cube can be visualized by dragging a square into the third dimension and watching the shape that the square traces through space, a tesseract is produced by the trail of a cube moving into the fourth dimension. Although it is difficult to visualize a cube being shifted a distance in a direction perpendicular to all three of its axes, computer graphics often help mathematicians develop a better intuition for higher-dimensional objects. Note that a cube is bounded by square faces and a tesseract by cubical faces. We can write down the number of corners, edges, faces, and solids for these kinds of higher-dimensional objects:

	Corners	Edges	Faces	Solids	Hypervolumes
Point	1	0	0	0	
Line segment	2	1	0	0	0
Square	4	4	1	0	0
Cube	8	12	6	1	0
Hypercube	16	32	24	8	1
Hyperhypercube	32	80	80	40	10

The word *tesseract* was coined and first used in 1888 by British mathematician Charles Howard Hinton in his book *A New Era of Thought*. Hinton, a bigamist, was also famous for his set of colored cubes that he claimed could be used to help people visualize the fourth dimension. When used at séances, the Hinton cubes were thought to help people glimpse ghosts of dead family members.

SEE ALSO Euclid's *Elements* (c. 300 BCE), Projective Geometry (1639), Möbius Strip (1858).

Rendering of a tesseract by Robert Webb using Stella4D software. The tesseract is the four-dimensional analog of the ordinary cube.



1890

Steam Turbine • *Marshall Brain*

Sir Charles Parsons (1854–1931)

If you go to any large power plant today, one of the landmarks will be a huge steam turbine bigger than a bus. You find steam turbines on aircraft carriers and nuclear submarines, too. With the steam turbine, engineers were able to reconceptualize the extraction of power from steam and thus abandon pistons.

Let's get in our time machine and go back to the engine room of the *Titanic* in 1912. Here they are using steam drawn from over one hundred massive coal-fired boilers and it is going into three steam engines driving three propellers. Two of these steam engines are gigantic piston machines that produce 30,000 hp (22 million watts) each, and the third is a steam turbine producing about half that. What we witness here is a period of transition. Steam turbines, first invented by Sir Charles Parsons in 1890, had not yet been perfected, but they would soon replace pistons to extract rotational energy from steam.

The basic idea behind a steam turbine is extremely simple. The expanding steam turns a series of vanes attached to a shaft. The vanes get progressively larger, so that the steam's energy can be captured as it expands. Compare that process to the *Titanic*'s piston engines; the piston engines use three cylinders of increasing size. The steam first expands in the smallest cylinder. Then it flows to the next cylinder, somewhat larger in size to extract more power from the less dense exhaust of cylinder one. Then to the third even larger cylinder. This worked but made for a large and heavy piece of equipment. One steam piston engine on the *Titanic* weighed 1,000 tons.

A steam turbine does the same job, but is much smaller, lighter, and more efficient than an equivalent steam piston engine. Modern steam turbines appear in almost every major coal-fired and nuclear power plant today because of these advantages. Instead of just three expansion chambers, the steam turbine can have many stages of vanes of increasing size to extract as much power as possible. This shows how engineers switch to completely new concepts to get better results.

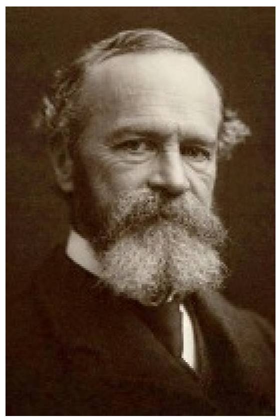
SEE ALSO Gears (c. 50), High-Pressure Steam Engine (1800), Carnot Engine (1824), Internal Combustion Engine (1908).

Installation of a turbine blade on a steam turbine rotor being assembled in a factory. Contemporary turbines are so precisely made that they can only be constructed with computers.

1890

The Principles of Psychology • *Wade E. Pickren*

William James (1842–1910)



Artistic by temperament, William James bowed to his father's wishes and was educated as a physician. He never practiced, however, and after a period of existential struggle he accepted an appointment as a lecturer at Harvard. There he pioneered the new field of psychology in America and wrote what proved to be the most influential text of his era, *The Principles of Psychology*. It took him twelve years to write, and after it was published in 1890, he wrote a friend, "Psychology is a damnable subject."

In *Principles*, James described psychology as the science of mental life. He wrote that the point of scientific psychology was to help us understand that consciousness and our minds evolved to help us adapt and survive in the world. Thus what consciousness does is more important than what it is or what it contains.

How might the mind best be studied? In Germany, the first laboratory psychologists were using refined mechanical instruments such as the Hipp chronoscope to measure mental reactions. James rejected this approach, as he believed that one could never understand the complexity of human mental life by adding up its contents or by measuring the speed of reactions. James offered an alternative view of consciousness. In a beautiful and enduring metaphor, he said consciousness is like a stream, dynamic and ever changing. A person, he wrote, could never step into the same river twice. Thus no instrument could ever capture this experience.

James also wrote about habit, calling it the "flywheel of life." He proposed a theory of emotions, that feelings follow behavior, which now is known as the James-Lange theory of emotions. (Carl Lange was a Danish physician who made the same suggestion independently but at about the same time.) James also argued for a pragmatic, pluralistic view of truth; those things are true, he argued, that help us in life.

James and his book have been the greatest influence on the development of American psychology to date. To indicate his breadth, it is worth noting his obituary headline in the *New York Times*: "William James Dies; Great Psychologist, brother of novelist, and foremost American philosopher was 68 years old. Long Harvard professor, virtual founder of modern American psychology, and exponent of pragmatism, dabbled in spooks."

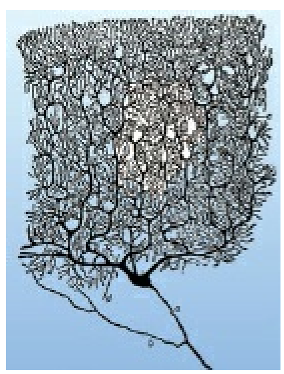
SEE ALSO Psychoanalysis (1899), Classical Conditioning (1903), Placebo Effect (1955), Cognitive Behavior Therapy (1963), Theory of Mind (1978).

LEFT: William James, c. 1890s. RIGHT: Tiber River at Rome, Italy, 2009. James used the phrase "stream of consciousness" as a metaphor for constantly changing mental processes.

1891

Neuron Doctrine • *Clifford A. Pickover*

Heinrich Wilhelm Gottfried von Waldeyer-Hartz (1836–1921), **Camillo Golgi** (1843–1926), **Santiago Ramón y Cajal** (1852–1934)



According to neurobiologist Gordon Shepherd, the Neuron Doctrine is "one of the great ideas of modern thought [comparable to] quantum theory and relativity in physics [and] the periodic table and the chemical bond in chemistry." Having its birth in microscopy studies in the late 1800s, the Neuron Doctrine posits that distinct cells called neurons serve as the functional signal units of the nervous system and that neurons connect to one another in several precise ways. The doctrine was formally stated in 1891 by German anatomist Wilhelm von Waldeyer-Hartz, based on the observations of Spanish neuroscientist Santiago Cajal, Italian pathologist Camillo Golgi, and other scientists. Cajal improved upon the special silver stains of Golgi that allowed them to better microscopically visualize the incredible detail of cell branching processes.

Although modern scientists have found exceptions to the original doctrine, most neurons contain dendrites, a soma (cell body), and an axon (which can be as long as three feet, or one meter!). In many cases, signals may propagate from one neuron to another by neurotransmitter chemicals that leave the axon of one neuron, travel through a tiny junction space called a chemical synapse, and then enter the dendrite of an adjacent neuron. If the net excitation caused by signals impinging on a neuron is sufficiently large, the neuron generates a brief electrical pulse called an action potential that travels along the axon. Electrical synapses, called gap junctions, also exist and create a direct connection between neurons.

Sensory neurons carry signals from sensory receptor cells in the body to the brain. Motor neurons transmit signals from the brain to muscles. Glial cells provide structural and metabolic support to the neurons. While neurons in adults tend not to reproduce, new connections between neurons can form throughout life. Each of the roughly 100 billion neurons can have more than 1,000 synaptic connections.

Multiple sclerosis results from insufficient myelin (chemical insulation) around axons. Parkinson's disease is associated with a lack of the neurotransmitter dopamine, normally produced by certain neurons in the midbrain.

SEE ALSO Cerebral Localization (1861), Antidepressant Medications (1957), Brain Lateralization (1964).

LEFT: *Cajal's complex drawing of a Purkinje neuron in a cat's cerebellar cortex.* RIGHT: *Neuron with multiple dendrites, a cell body, and one long axon. The capsulelike bulges on the axon are myelin-sheath cells.*

1892

Discovery of Viruses • *Clifford A. Pickover*

Martinus Willem Beijerinck (1851–1931), **Dimitri Iosifovich Ivanovsky** (1864–1920)

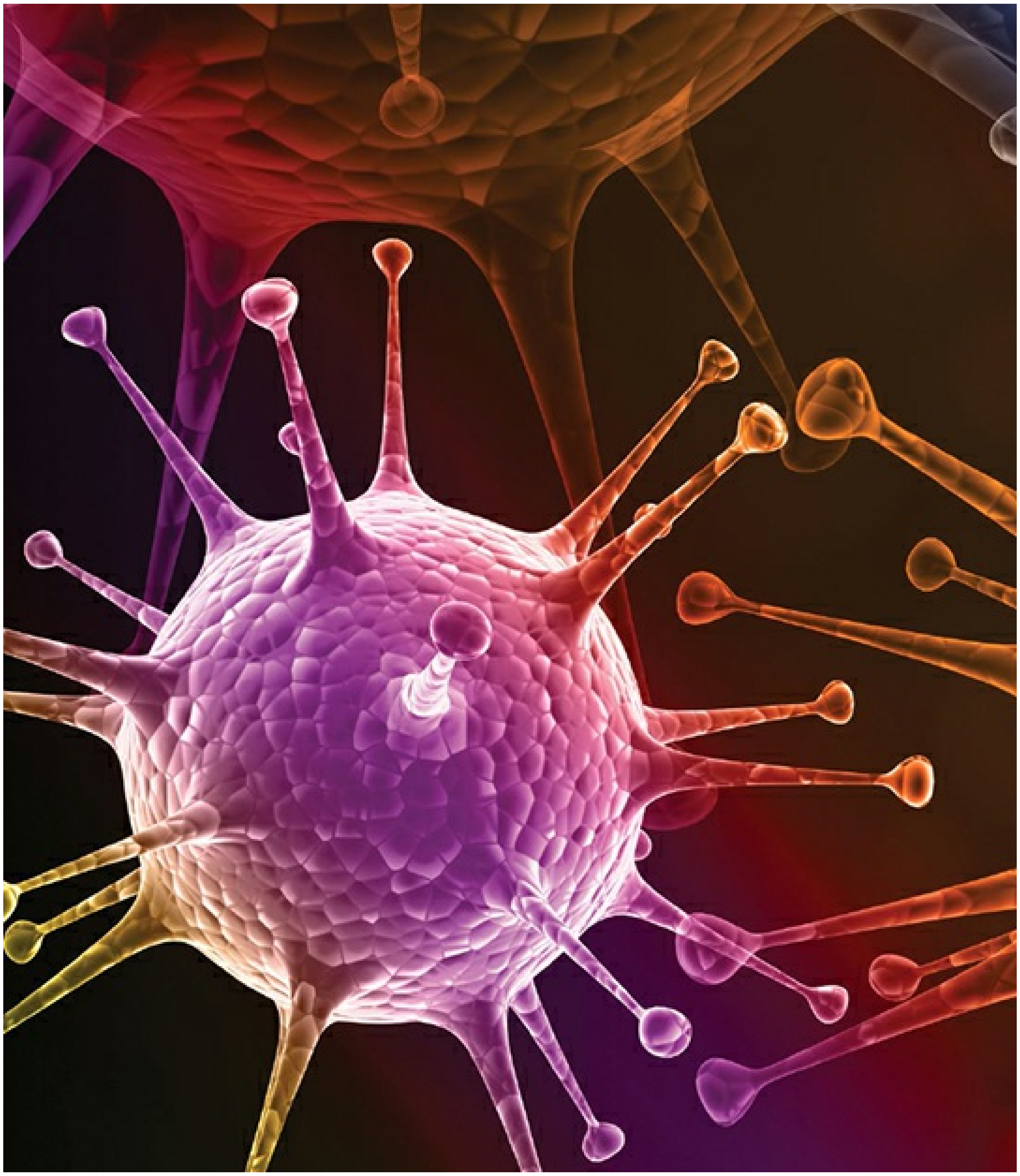
Science journalist Robert Adler writes, “Rabies, smallpox, yellow fever, dengue fever, poliomyelitis, influenza, AIDS . . . The list [of diseases caused by viruses] reads like a catalog of human misery. . . . The scientists who deciphered the secrets of viruses were literally groping in the dark, trying to understand something they could not see . . . and, for many years, could not even imagine.”

Viruses exist in a strange realm between the living and nonliving. They do not possess all of the required molecular machinery to reproduce themselves on their own, but once they infect animals, plants, fungi, or bacteria, they can hijack their hosts in order to generate numerous viral copies. Some viruses may coax their host cells into uncontrolled multiplication, leading to cancer. Today, we know that most viruses are too small to be seen by an ordinary light microscope, given that an average virus is about one one-hundredth the size of the average bacterium. The virions (virus particles) consist of genetic material in the form of DNA or RNA and an outer protein coating. Some viruses also have an envelope of lipids (small organic molecules) when the virus is outside a host cell.

In 1892, Russian biologist Dimitri Ivanovsky took one of the early steps toward understanding viruses when he attempted to understand the cause of tobacco mosaic disease, which destroys tobacco leaves. He filtered an extract of crushed diseased leaves by using a fine porcelain filter designed to trap all bacteria. To his surprise, the fluid that had flowed through the filter was still infectious. However, Ivanovsky never understood the true viral cause, believing that toxins or bacterial spores might be the causative agent. In 1898, Dutch microbiologist Martinus Beijerinck performed a similar experiment and believed that this new kind of infectious agent was liquid in nature, referring to it as “soluble living germs.” Later researchers were able to grow viruses in media containing guinea pig cornea tissue, minced hen kidneys, and fertilized chicken eggs. It was not until the 1930s that viruses could finally be seen via the electron microscope.

SEE ALSO Germ Theory of Disease (1862), HeLa Cells (1951), Structure of Antibodies (1959).

Most animal viruses are symmetrical (e.g., icosahedral) and nearly spherical in shape, as depicted in this artistic representation. Viruses are generally much smaller than bacteria.



1895

X-rays • *Clifford A. Pickover*

Wilhelm Conrad Röntgen (1845–1923), **Max von Laue** (1879–1960)

Upon seeing her husband's X-ray image of her hand, Wilhelm Röntgen's wife "shrieked in terror and thought that the rays were evil harbingers of death," writes author Kendall Haven. "Within a month, Wilhelm Röntgen's X-rays were the talk of the world. Skeptics called them death rays that would destroy the human race. Eager dreamers called them miracle rays that could make the blind see again and could beam . . . diagrams straight into a student's brains." However, for physicians, X-rays marked a turning point in the treatment of the sick and wounded.

On November 8, 1895, the German physicist Wilhelm Röntgen was experimenting with a cathode-ray tube when he found that a discarded fluorescent screen lit up over a meter away when he switched on the tube, even though the tube was covered with a heavy cardboard. He realized that some form of invisible ray was coming from the tube, and he soon found that they could penetrate various materials, including wood, glass, and rubber. When he placed his hand in the path of the invisible rays, he saw a shadowy image of his bones. He called the rays *X-rays* because they were unknown and mysterious at that time, and he continued his experiments in secrecy in order to better understand the phenomena before discussing them with other professionals. For his systematic study of X-rays, Röntgen would win the first Nobel Prize.

Physicians quickly made use of X-rays for diagnoses, but the precise nature of X-rays was not fully elucidated until around 1912, when Max von

Laue used X-rays to create a diffraction pattern of a crystal, which verified that X-rays were electromagnetic waves, like light, but of a higher energy and a shorter wavelength that was comparable to the distance between atoms in molecules. Today, X-rays are used in countless fields, ranging from X-ray crystallography (to reveal the structure of molecules) to X-ray astronomy (e.g., the use of X-ray detectors on satellites to study X-ray emissions from sources in outer space).

SEE ALSO Telescope (1608), Wave Nature of Light (1801), Electromagnetic Spectrum (1864), Radioactivity (1896).

X-ray of the side view of a human head, showing screws used to reconstruct the jaw bones.

1896

Proof of the Prime Number Theorem •

Clifford A. Pickover

Johann Carl Friedrich Gauss (1777–1855), **Jacques Salomon Hadamard** (1865–1963), **Charles-Jean de la Vallée-Poussin** (1866–1962), **John Edensor Littlewood** (1885–1977)

Mathematician Don Zagier has commented that “despite their simple definition and role as the building blocks of the natural numbers, the prime numbers grow like weeds among the natural numbers . . . and nobody can predict where the next one will sprout. . . . Even more astonishing . . . the prime numbers exhibit stunning regularity, there are laws governing their behavior, and they obey these laws with almost military precision.”

Consider $\pi(n)$, which is the number of primes less than or equal to a given number n. In 1792, when only 15 years old, Carl Gauss became fascinated by the occurrence of prime numbers, and he proposed that $\pi(n)$ was approximately equal to $n/\ln(n)$, where ln is the natural logarithm. One consequence of the prime number theorem is that the nth prime number is approximately equal to $n\ln(n)$, with the relative error of this approximation approaching 0 as n approaches infinity. Gauss later refined his estimate to $\pi(n) \sim \mathrm{Li}(n)$ where $\mathrm{Li}(n)$ is the integral from 2 to n of $dx/\ln(x)$.

Finally, in 1896, French mathematician Jacques Hadamard and Belgian mathema-tician Charles-Jean de la Vallée-Poussin independently proved Gauss’s theorem. Based on numerical experiments, mathematicians had conjectured that $\pi(n)$ was always somewhat less than $\mathrm{Li}(n)$. However, in

1914, Littlewood proved that $\pi(n) < \mathrm{Li}(n)$ reverses *infinitely* often if one were able to search though huge values of *n*. In 1933, South African mathematician Stanley Skewes showed that the first crossing of $\pi(n) - \mathrm{Li}(n) = 0$ occurs before 10^10^10^34, a number referred to as Skewes' number, where ^ indicates the raising to a power. Since 1933, this value has been reduced to around 10^{316}.

English mathematician G. H. Hardy (1877–1947) once described Skewes' number as "the largest number which has ever served any definite purpose in mathematics," although the Skewes' number has since lost this lofty accolade. Around 1950, Paul Erdös and Atle Selberg discovered an elementary proof of the prime number theorem—that is, a proof that uses only real numbers.

SEE ALSO Sieve of Eratosthenes (c. 240 BCE) Riemann Hypothesis (1859), Public-Key Cryptography (1977), Proof of the Kepler Conjecture (2017).

Prime numbers, represented in boldface, "grow like weeds among the natural numbers . . . and nobody can predict where the next one will sprout. . . ." Although the number 1 used to be considered a prime, today mathematicians generally consider 2 to be the first prime.

1, **2**, **3**, 4, **5**, 6, **7**, 8, 9, 10, **11**, 12, **13**, 14, 15, 16, **17**, 18, **19**, 20, 21, 22, **23**, 24, 25, 26, 27, 28, **29**, 30, **31**, 32, 33, 34, 35, 36, **37**, 38, 39,
40, **41**, 42, **43**, 44, 45, 46, **47**, 48, 49, 50, 51, 52, **53**, 54, 55, 56, 57, 58, **59**, 60, **61**, 62, 63, 64, 65, 66, **67**, 68, 69, 70, **71**, 72, **73**, 74, 75,
76, 77, 78, **79**, 80, 81, 82, **83**, 84, 85, 86, 87, 88, **89**, 90, 91, 92, 93, 94, 95, 96, **97**, 98, 99, 100, **101**, 102, **103**, 104, 105, 106, **107**, 108,
109, 110, 111, 112, **113**, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, **127**, 128, 129, 130, **131**, 132, 133, 134, 135,
136, **137**, 138, **139**, 140, 141, 142, 143, 144, 145, 146, 147, 148, **149**, 150, **151**, 152, 153, 154, 155, 156, **157**, 158, 159, 160, 161, 162,
163, 164, 165, 166, **167**, 168, 169, 170, 171, 172, **173**, 174, 175, 176, 177, 178, **179**, 180, **181**, 182, 183, 184, 185, 186, 187, 188, 189,
190, **191**, 192, **193**, 194, 195, 196, **197**, 198, **199**, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 210, **211**, 212, 213, 214, 215, 216,
217, 218, 219, 220, 221, 222, **223**, 224, 225, 226, **227**, 228, **229**, 230, 231, 232, **233**, 234, 235, 236, 237, 238, **239**, 240, **241**, 242, 243,
244, 245, 246, 247, 248, 249, 250, **251**, 252, 253, 254, 255, 256, **257**, 258, 259, 260, 261, 262, **263**, 264, 265, 266, 267, 268, **269**, 270,
271, 272, 273, 274, 275, 276, **277**, 278, 279, 280, **281**, 282, **283**, 284, 285, 286, 287, 288, 289, 290, 291, 292, **293**, 294, 295, 296, 297,
298, 299, 300, 301, 302, 303, 304, 305, 306, **307**, 308, 309, 310, **311**, 312, **313**, 314, 315, 316, **317**, 318, 319, 320, 321, 322, 323, 324,
325, 326, 327, 328, 329, 330, **331**, 332, 333, 334, 335, 336, **337**, 338, 339, 340, 341, 342, 343, 344, 345, 346, **347**, 348, **349**, 350, 351,
352, **353**, 354, 355, 356, 357, 358, **359**, 360, 361, 362, 363, 364, 365, 366, **367**, 368, 369, 370, 371, 372, **373**, 374, 375, 376, 377, 378,
379, 380, 381, 382, **383**, 384, 385, 386, 387, 388, **389**, 390, 391, 392, 393, 394, 395, 396, **397**, 398, 399, 400, **401**, 402, 403, 404, 405,
406, 407, 408, **409**, 410, 411, 412, 413, 414, 415, 416, 417, 418, **419**, 420, **421**, 422, 423, 424, 425, 426, 427, 428, 429, 430, **431**, 432,
433, 434, 435, 436, 437, 438, **439**, 440, 441, 442, **443**, 444, 445, 446, 447, 448, **449**, 450, 451, 452, 453, 454, 455, 456, **457**, 458, 459,
460, **461**, 462, **463**, 464, 465, 466, **467**, 468, 469, 470, 471, 472, 473, 474, 475, 476, 477, 478, **479**, 480, 481, 482, 483, 484, 485, 486,
487, 488, 489, 490, **491**, 492, 493, 494, 495, 496, 497, 498, **499**, 500, 501, 502, **503**, 504, 505, 506, 507, 508, **509**, 510, 511, 512, 513,
514, 515, 516, 517, 518, 519, 520, **521**, 522, **523**, 524, 525, 526, 527, 528, 529, 530, 531, 532, 533, 534, 535, 536, 537, 538, 539, 540,
541, 542, 543, 544, 545, 546, **547**, 548, 549, 550, 551, 552, 553, 554, 555, 556, **557**, 558, 559, 560, 561, 562, **563**, 564, 565, 566, 567,
568, **569**, 570, **571**, 572, 573, 574, 575, 576, **577**, 578, 579, 580, 581, 582, 583, 584, 585, 586, **587**, 588, 589, 590, 591, 592, **593**, 594,
595, 596, 597, 598, **599**, 600, **601**, 602, 603, 604, 605, 606, **607**, 608, 609, 610, 611, 612, **613**, 614, 615, 616, **617**, 618, **619**, 620, 621,
622, 623, 624, 625, 626, 627, 628, 629, 630, **631**, 632, 633, 634, 635, 636, 637, 638, 639, 640, **641**, 642, **643**, 644, 645, 646, **647**, 648,
649, 650, 651, 652, **653**, 654, 655, 656, 657, 658, **659**, 660, **661**, 662, 663, 664, 665, 666, 667, 668, 669, 670, 671, 672, **673**, 674, 675,
676, **677**, 678, 679, 680, 681, 682, **683**, 684, 685, 686, 687, 688, 689, 690, **691**, 692, 693, 694, 695, 696, 697, 698, 699, 700, **701**, 702,
703, 704, 705, 706, 707, 708, **709**, 710, 711, 712, 713, 714, 715, 716, 717, 718, **719**, 720, 721, 722, 723, 724, 725, 726, **727**, 728, 729,
730, 731, 732, **733**, 734, 735, 736, 737, 738, **739**, 740, 741, 742, **743**, 744, 745, 746, 747, 748, 749, 750, **751**, 752, 753, 754, 755, 756,
757, 758, 759, 760, **761**, 762, 763, 764, 765, 766, 767, 768, **769**, 770, 771, 772, **773**, 774, 775, 776, 777, 778, 779, 780, 781, 782, 783,
784, 785, 786, **787**, 788, 789, 790, 791, 792, 793, 794, 795, 796, **797**, 798, 799, 800, 801, 802, 803, 804, 805, 806, 807, 808, **809**, 810,
811, 812, 813, 814, 815, 816, 817, 818, 819, 820, **821**, 822, **823**, 824, 825, 826, **827**, 828, **829**, 830, 831, 832, 833, 834, 835, 836, 837,
838, **839**, 840, 841, 842, 843, 844, 845, 846, 847, 848, 849, 850, 851, 852, **853**, 854, 855, 856, **857**, 858, **859**, 860, 861, 862, **863**, 864,
865, 866, 867, 868, 869, 870, 871, 872, 873, 874, 875, 876, **877**, 878, 879, 880, **881**, 882, **883**, 884, 885, 886, **887**, 888, 889, 890, 891,
892, 893, 894, 895, 896, 897, 898, 899, 900, 901, 902, 903, 904, 905, 906, **907**, 908, 909, 910, **911**, 912, 913, 914, 915, 916, 917, 918,
919, 920, 921, 922, 923, 924, 925, 926, 927, 928, **929**, 930, 931, 932, 933, 934, 935, 936, **937**, 938, 939, 940, **941**, 942, 943, 944, 945,
946, **947**, 948, 949, 950, 951, 952, **953**, 954, 955, 956, 957, 958, 959, 960, 961, 962, 963, 964, 965, 966, **967**, 968, 969, 970, **971**, 972,
973, 974, 975, 976, **977**, 978, 979, 980, 981, 982, **983**, 984, 985, 986, 987, 988, 989, 990, **991**, 992, 993, 994, 995, 996, **997**, 998, 999

1896

Radioactivity • *Clifford A. Pickover*

Abel Niépce de Saint-Victor (1805–1870), **Antoine Henri Becquerel** (1852–1908), **Pierre Curie** (1859–1906), **Marie Skłodowska Curie** (1867–1934), **Ernest Rutherford** (1871–1937), **Frederick Soddy** (1877–1956)

To understand the behavior of radioactive nuclei (the central regions of atoms), picture popcorn popping on your stove. Kernels appear to pop at random over several minutes, and a few don't seem to pop at all. Similarly, most familiar nuclei are stable and are essentially the same now as they were centuries ago. However, other kinds of nuclei are unstable and spew fragments as the nuclei disintegrate. Radioactivity is the emission of such particles.

The discovery of radioactivity is usually associated with French scientist Henri Becquerel's 1896 observations of phosphorescence in uranium salts. Roughly a year before Becquerel's discovery, German physicist Wilhelm Röntgen discovered X-rays while experimenting with electrical discharge tubes, and Becquerel was curious to see if phosphorescent compounds (compounds that emit visible light after being stimulated by sunlight or other excitation waves) might also produce X-rays. Becquerel placed uranium potassium sulfate on a photographic plate that was wrapped in black paper. He wanted to see if this compound would phosphoresce and produce X-rays when stimulated by light.

To Becquerel's surprise, the uranium compound darkened the photographic plate even when the packet was in a drawer. Uranium seemed to be emitting some kind of penetrating "rays." In 1898, physicists Marie and

Pierre Curie discovered two new radioactive elements, polonium and radium. Sadly, the dangers of radioactivity were not immediately recognized, and some physicians began to provide radium enema treatments among other dangerous remedies. Later, Ernest Rutherford and Frederick Soddy discovered that these kinds of elements were actually transforming into other elements in the radioactive process.

Scientists were able to identify three common forms of radioactivity: alpha particles (bare helium nuclei), beta rays (high-energy electrons), and gamma rays (high-energy electromagnetic rays). Author Stephen Battersby notes that, today, radioactivity is used for medical imaging, killing tumors, dating ancient artifacts, and preserving food.

SEE ALSO X-rays (1895), $E = mc^2$ (1905), Neutron (1932), Energy from the Nucleus (1942), Little Boy Atomic Bomb (1945), Radiocarbon Dating (1949).

During the late 1950s, fallout shelters grew in number across the US. These spaces were designed to protect people from radioactive debris from a nuclear explosion. In principle, people might remain in the shelters until the radioactivity had decayed to a safer level outside.


CAPACITY
FALLOUT SHELTER

1897

Electron • *Clifford A. Pickover*

Joseph John “J. J.” Thomson (1856–1940)

“The physicist J. J. Thomson loved to laugh,” writes author Josepha Sherman. “But he was also clumsy. Test tubes broke in his hands, and experiments refused to work.” Nevertheless, we are lucky that Thomson persisted and revealed what Benjamin Franklin and other physicists had suspected—that electrical effects were produced by minuscule units of electrical charge. In 1897, J. J. Thomson identified the electron as a distinct particle with a mass much smaller than the atom. His experiments employed a cathode ray tube: an evacuated tube in which a beam of energy travels between a positive and negative terminal. Although no one was sure what cathode rays actually were at the time, Thompson was able to bend the rays using a magnetic field. By observing how the cathode rays moved through electric and magnetic fields, he determined that the particles were identical and did not depend on the metal that emitted them. Also, the particles all had the same ratio of electric charge to mass. Others had made similar observations, but Thomson was among the first to suggest that these “corpuscles” were the carriers of all forms of electricity and a basic component of matter.

Discussions of the various properties of electrons are presented in many sections of this book. Today, we know that the electron is a subatomic particle with negative electric charge and a mass that is 1/1,836 of the mass of a proton. An electron in motion generates a magnetic field. An attractive force, known as the Coulomb force, between the positive proton and the negative electron causes electrons to be bound to atoms. Chemical bonds between atoms may result when two or more electrons are shared between atoms.

According to the American Institute of Physics, “Modern ideas and technologies based on the electron, leading to the television and the computer and much else, evolved through many difficult steps. Thomson’s careful experiments and adventurous hypotheses were followed by crucial experimental and theoretical work by many others [who] opened for us new perspective—a view from *inside* the atom.”

SEE ALSO Battery (1800), Wave Nature of Light (1801), Atomic Theory (1808), Photoelectric Effect (1905), Bohr Atom (1913), De Broglie Relation (1924), Pauli Exclusion Principle (1925), Schrödinger’s Wave Equation (1926), Dirac Equation (1928).

A lightning discharge involves a flow of electrons. The leading edge of a bolt of lightning can travel at speeds of 130,000 miles per hour (60,000 meters/second) and can reach temperatures approaching 54,000°F (30,000°C).

1899

Psychoanalysis • *Clifford A. Pickover*

Sigmund Freud (1856–1939)

According to author Catherine Reef, the Austrian physician Sigmund Freud "explored the human mind more thoroughly than anyone who had come before him. He pioneered a new method for diagnosing and treating mental illness, a method he called psychoanalysis. He simply talked to his patients, and, more important, he listened." Freud emphasized the importance of unconscious mental processes in shaping human behavior and emotions, and he encouraged his patients to "freely associate" and speak about images from fantasies and dreams. He encouraged patients to act as though they were travelers "sitting next to the window of a railway carriage and describing to someone outside the carriage the changing views" seen outside. When waiting for his patients' words to reveal hidden messages, Freud often felt like an archeologist unearthing precious relics in ancient cities. His goal was to interpret unconscious conflicts that caused harmful symptoms, thereby giving the patients insight and resolutions to their problems, which might include abnormal fears or obsessions. *The Interpretation of Dreams*, published in 1899, was his greatest work.

In general, Freud often suggested that patients' repressed sexual fantasies and early childhood experiences played an important role in later dysfunctional behavior. His most famous psychoanalytic model divided the mind into three separate parts: the id (concerned with basic drives such as sexual satisfaction), the superego (concerned with socially acquired controls and moral codes), and the ego (the conscious mind that motivates our decisions through the tension between the id and superego).

Although it is still difficult to discern what fraction of his often controversial ideas will ultimately be considered correct or even useful, his ideas on psychology "have completely revolutionized our conception of the human mind," according to author Michael Hart. Rather than condemn or ridicule those with behavioral anomalies, Freud sought understanding. Psychiatrist Anthony Storr writes, "Freud's technique of listening to distressed people over long periods rather than giving them orders or advice has formed the foundation of most modern forms of psychotherapy, with benefits to both patients and practitioners."

SEE ALSO Cerebral Localization (1861), *The Principles of Psychology* (1890), Classical Conditioning (1903), Brain Lateralization (1964), Placebo Effect (1955), Antidepressant Medications (1957), Cognitive Behavior Therapy (1963), Theory of Mind (1978).

Freud's psychoanalytic couch, on which his patients reclined. Freud would sit out of sight in the green chair, listening to their free associations. (Freud Museum, London.)

1900

Blackbody Radiation Law • *Clifford A. Pickover*

Max Karl Ernst Ludwig Planck (1858–1947), **Gustav Robert Kirchhoff** (1824–1887)

“Quantum mechanics is magic,” writes quantum physicist Daniel Greenberger. Quantum theory, which suggests that matter and energy have the properties of both particles and waves, had its origin in pioneering research concerning hot objects that emit radiation. For example, imagine the coil on an electric heater that glows brown and then red as it gets hotter. The Blackbody Radiation Law, proposed by German physicist Max Planck in 1900, quantifies the amount of energy emitted by blackbodies at a particular wavelength. Blackbodies are objects that emit and absorb the maximum possible amount of radiation at any given wavelength and at any given temperature.

The amount of thermal radiation emitted by a blackbody changes with frequency and temperature, and many of the objects that we encounter in our daily lives emit a large portion of their radiation spectrum in the infrared, or far-infrared, portion of the spectrum, which is not visible to our eyes.

However, as the temperature of a body increases, the dominant portion of its spectrum shifts so that we can see a glow from the object.

In the laboratory, a blackbody can be approximated using a large, hollow, rigid object such as a sphere, with a hole poked in its side. Radiation entering the hole reflects off the inner walls, dissipating with each reflection as the walls absorb the radiation. By the time the radiation exits through the same hole, its intensity is negligible. Thus, this hole acts as a blackbody. Plank modeled the cavity walls of blackbodies as a collection of tiny electromagnetic oscillators. He posited that the energy of oscillators is discrete and could assume only certain values. These oscillators both *emit* energy into the cavity and *absorb* energy from it via discrete jumps, or in packages called quanta. Planck's quantum approach involving discrete oscillator energies for theoretically deriving his Radiation Law led to his 1918 Nobel Prize. Today, we know that the universe was a near-perfect blackbody right after the Big Bang. German physicist Gustav Kirchhoff introduced the actual term *blackbody* in 1860.

SEE ALSO Electromagnetic Spectrum (1864), Photoelectric Effect (1905), Cosmic Microwave Background (1965).

LEFT: *Max Planck, 1878.* RIGHT: *Molten glowing lava is an approximation of blackbody radiation, and the temperature of the lava can be estimated from the color.*

1900

Hilbert’s 23 Problems • *Clifford A. Pickover*

David Hilbert (1862–1943)

German mathematician David Hilbert wrote, “A branch of science is full of life as long as it offers an abundance of problems; a lack of problems is a sign of death.” In 1900, he presented 23 important mathematical problems to be targeted for solution in the twentieth century. Because of Hilbert’s prestige, mathematicians spent a great deal of time tackling the problems through the years. His extremely influential speech on the subject started, “Who of us would not be glad to lift the veil behind which the future lies hidden; to cast a glance at the next advances of our science and at the secrets of its development during future centuries? What particular goals will there be toward which the leading mathematical spirits of coming generations will strive?”

About ten of the problems have since been cleanly solved, and many others have solutions that are accepted by some mathematicians but for which some controversy still remains. For example, the Kepler Conjecture (part of Problem 18), which raised questions about the efficiency of sphere packing, involved a computer-assisted proof, which was difficult for people to verify. Finally, in 2017, the *Forum of Mathematics, Pi* journal published a formal proof of the Kepler Conjecture, by a team led by American mathematician Thomas Hales, resolving a problem that was unsolved for hundreds of years.

One of the most famous problems still unresolved today is the Riemann Hypothesis, which concerns the distribution of the zeros of the Riemann zeta function (a very wiggly function). David Hilbert remarked, “If I were to awaken after having slept for a thousand years, my first question would be: Has the Riemann hypothesis been proven?”

Ben Yandell writes, “Solving one of Hilbert’s Problems has been the romantic dream of many a mathematician. . . . In the last hundred years, solutions and significant partial results have come from all over the world. Hilbert’s list is a thing of beauty, and aided by their romantic and historical appeal, these well-chosen problems have been an organizing force in mathematics.”

SEE ALSO Riemann Hypothesis (1859), Cantor’s Transfinite Numbers (1874), Proof of the Prime Number Theorem (1896), Noether’s *Idealtheorie* (1921), Proof of the Kepler Conjecture (2017).

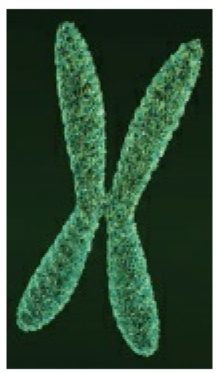
Photograph of David Hilbert (1912), which appeared on postcards of faculty members at the University of Göttingen. Students often purchased such postcards.

1902

Chromosomal Theory of Inheritance •

Clifford A. Pickover

Theodor Heinrich Boveri (1862–1915), Walter Stanborough Sutton (1877–1916)



Chromosomes are threadlike structures, each made of a long coiled DNA molecule wrapped around a protein scaffold. Chromosomes are visible under a microscope during cell division. Human body cells contain 23 pairs of chromosomes—one member of the pair contributed by the mother and one by the father. Sperm and egg each contain 23 unpaired chromosomes. When the egg is fertilized, the number of chromosomes is restored to 46.

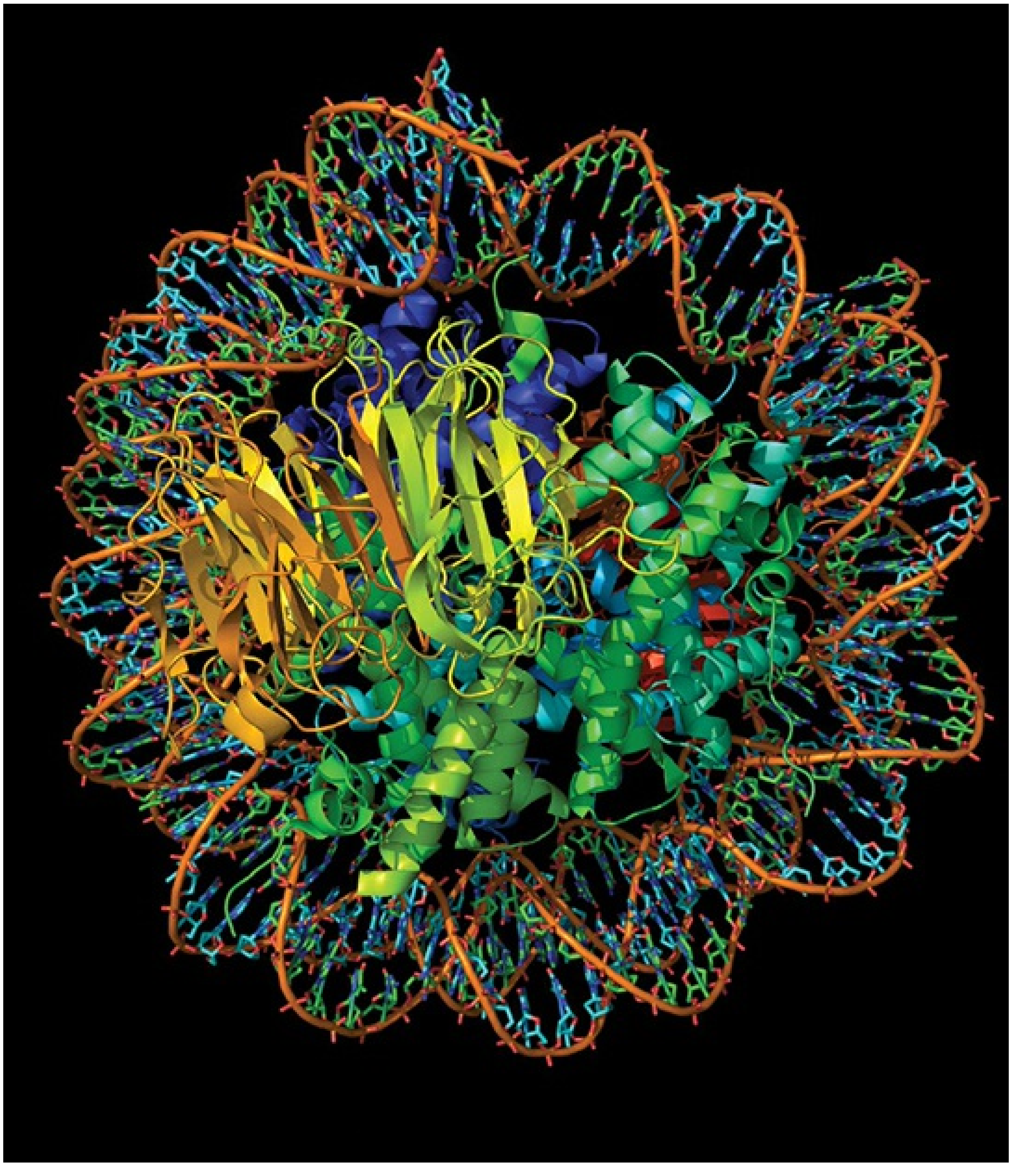
Around 1865, Austrian priest Gregor Mendel observed that organisms inherit traits via discrete units that we now refer to as genes, but it was not until 1902 that German biologist Theodor Boveri and American geneticist and physician Walter Sutton independently identified chromosomes as the carrier of this genetic information.

While studying sea urchins, Boveri concluded that sperm and egg each had a half set of chromosomes. However, if sperm and egg united to create sea urchin embryos with abnormal numbers of chromosomes, the embryos developed abnormally. Boveri concluded that different chromosomes affected different aspects of the creatures' development. Sutton's studies of grasshoppers demonstrated that matched pairs of chromosomes separate during the generation of sex cells. Not only did Boveri and Sutton suggest that the chromosomes carry parental genetic information, they also showed that chromosomes were independent entities that persisted even when they were not visible, during various stages of a cell's life, which was counter to one prevailing belief that the chromosomes simply "dissolved" during the course of cell division and reformed in the daughter cells. Their work provided a foundation for the new field of cytogenetics, the combination of cytology (the study of cells) and genetics (the science of heredity).

Today we know that during the creation of sperm and egg, matching chromosomes of parents can exchange small parts in a "crossover" process, so that new chromosomes are not inherited solely from either parent. Incorrect numbers of chromosomes can lead to genetic disorders. People with Down syndrome have 47 chromosomes.

SEE ALSO Discovery of Sperm (1678), Cell Division (1855), Mendel's Genetics (1865), HeLa Cells (1951), DNA Structure (1953), Epigenetics (1983), Human Genome Project (2003).

LEFT: *Artist's representation of a chromosome.* RIGHT: *Within each chromosome, strands of DNA are coiled around proteins to form a nucleosome (shown here). Nucleosomes, in turn, are folded into even more complex structures within the chromosome, thus providing additional regulatory control of gene expression.*



1903

Wright Brothers' Airplane • *Marshall Brain*

Wilbur Wright (1867–1912), **Orville Wright** (1871–1948)

Airplanes are so familiar today that it's hard to imagine life without them. But at the start of the twentieth century, there was not a single airplane in existence. Many believed that humans would never fly.

The Wright brothers made the dream of flight a reality in North Carolina in 1903. They certainly were engineers, but they were also scientists and inventors. There were so many problems and fundamental questions that they needed to resolve: How to create lift? How to generate sufficient thrust? How to control flight? How to make the plane light enough? How to combine it all together?

For example, they built a wind tunnel and did fundamental research to discover wing shapes that provided maximum lift. Then they had to render those shapes as strong, lightweight structures—the bi-wing arrangement of the original Wright flyer using wood, fabric, and wire. Then they had to bend those structures during flight to control the plane. We look at their solution today as slightly bizarre—the entire wing warped, and they controlled warping with their hips. We consider their forward-mounted control surfaces to be strange as well. That's because the Wright Brothers started with a blank sheet of paper, with everything unprecedented and unknown. The conventions of rudder, elevator, and ailerons would evolve quickly once the brothers unlocked the core secrets of flight.

The entire aircraft weighed 605 pounds (275 kg) empty. How to get it off the ground? The engine seems primitive by today's standards. At 200 cubic inches (3.3 liters) and roughly 200 pounds (91 kg), it produced just 12 horsepower (9,000 watts). A small pan of gasoline in the engine’s air intake served as a carburetor, contact breakers in the cylinders created the spark, and evaporating water cooled the engine. A man named Charles Taylor built it from scratch from a three-way dialog with the brothers. But it reliably produced its 12 horsepower to spin two counter-rotating, hand-carved wooden propellers.

It seems nearly impossible that three people could bring so many ideas and engineering disciplines together to create a flying machine that worked. Inspiration, curiosity, persistence, and the thrill of discovery powered them through.

SEE ALSO Internal Combustion Engine (1908), First Humans in Space (1961), Saturn V Rocket (1967).

Pictured: The first sustained flight of the Wright Brothers’ airplane.

1903

Classical Conditioning • *Wade E. Pickren*

Ivan Pavlov (1849–1936)

Russian physiologist Ivan Pavlov insisted that the scientific study of the nervous system and its expressions must be objective, mechanistic, and materialistic in orientation. Pavlov was born and reared in central Russia, the son of a village priest. Initially, it seemed as though Pavlov would follow in his father's footsteps, but a growing personal interest in science led him to the University of Saint Petersburg, where he earned a degree in physiology.

By 1890, Pavlov was the director of the department of physiology at the university's Institute of Experimental Medicine. Pavlov's specialty was the study of digestion, for which he was awarded the Nobel Prize in physiology or medicine in 1904. Dogs were Pavlov's subject of choice for his experiments. When his work on digestion in the stomach came to an end, Pavlov began to study salivation as a necessary part of the digestive processes. In 1903, one of the dog handlers in Pavlov's laboratory observed that the dogs began salivation even before they were fed. When this came to Pavlov's attention, he experimentally investigated what he called the “psychic processes” involved in the phenomenon.

Pavlov explored how external stimuli could be manipulated to control behavior. His most famous example came to be called classical conditioning in English. It was a convincing demonstration that when a ringing bell is presented in association with the offering of food, dogs will become conditioned, or learn, to salivate even without food being offered. Pavlov claimed that such conditioning was a matter of processes in the nervous system itself and not a matter of the mind. Thus learning in the dog, and by extension in humans and other animals, was a matter of forming elementary associations that then led to the formation of chains of associations. For many years, Pavlov and his team explored the implications of his model of learning, including how it might explain mental disorders.

SEE ALSO *The Principles of Psychology* (1890), Psychoanalysis (1899), Placebo Effect (1955), Cognitive Behavior Therapy (1963), Theory of Mind (1978).

ABOVE: *Ivan Pavlov in his laboratory, 1922.* RIGHT: *Bronze statue of Pavlov and one of his dogs, located on the grounds of his laboratory in Koltushi, Russia.*

1905

$E = mc^2$ • *Clifford A. Pickover*

Albert Einstein (1879–1955)

"Generations have grown up knowing that the equation $E = mc^2$ changed the shape of our world," writes author David Bodanis, ". . . governing, as it does, everything from the atomic bomb to a television's cathode ray tube to the carbon dating of prehistoric paintings." Of course, part of the equation's appeal, independent from its meaning, is its simplicity. Physicist Graham Farmelo writes, "Great equations also share with the finest poetry an extraordinary power—poetry is the most concise and highly charged form of language, just as the great equations of science are the most succinct form of understanding of the aspect of physical reality they describe."

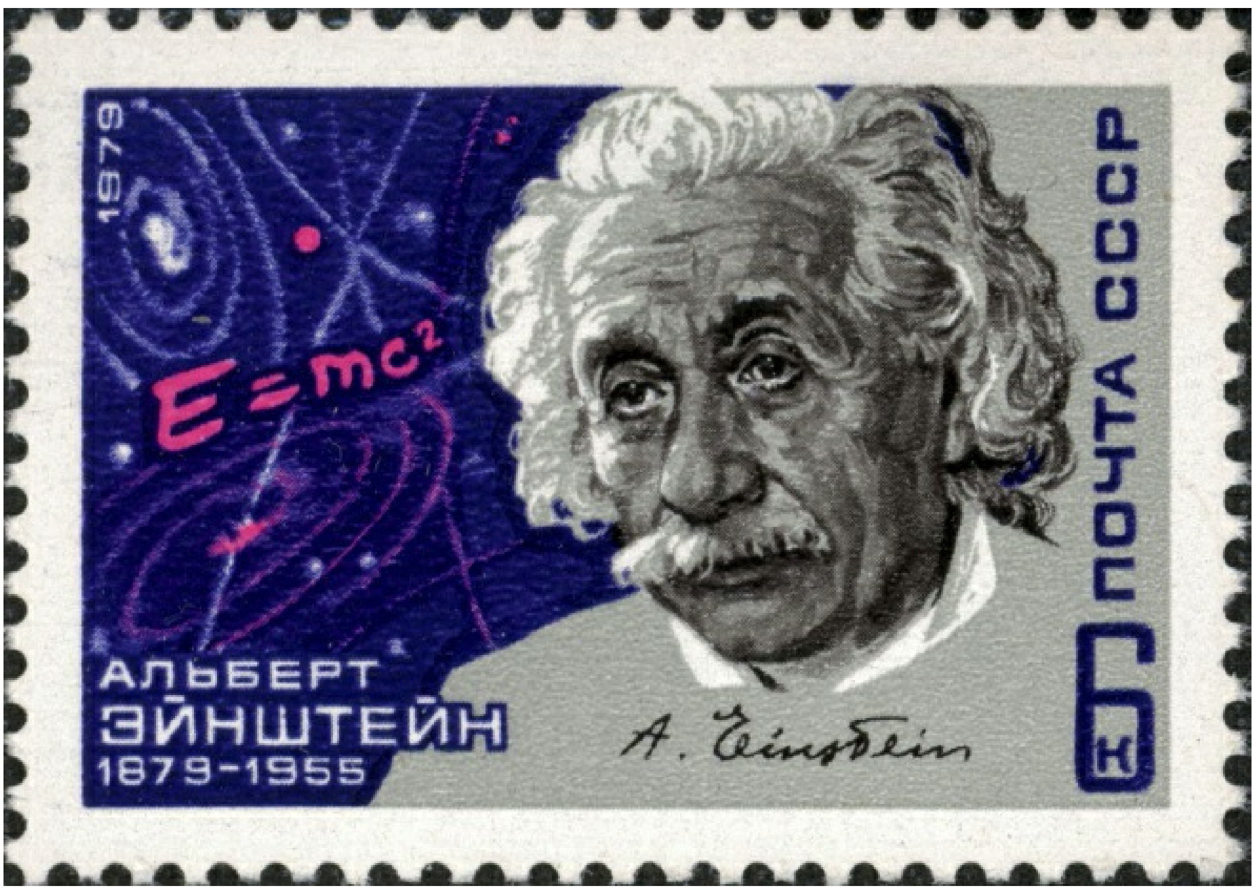
In a short article published in 1905, Einstein derived his famous $E = mc^2$, sometimes called the law of mass-energy equivalence, from the principles of Special Relativity. In essence, the formula indicates that the mass of a body is a "measure" of its energy content. c is the speed of light in vacuum, which is about 186,000 miles per second (299,792,468 meters per second).

Radioactive elements are constantly converting part of their masses to energy as governed by $E = mc^2$, and the formula was also used in the development of the atomic bomb to better understand the nuclear binding energy that holds the atomic nucleus together, which can be used to determine the energy released in a nuclear reaction.

$E = mc^2$ explains why the Sun shines. In the Sun, four hydrogen nuclei (four protons) are fused into a helium nucleus, which is less massive than the hydrogen nuclei that combine to make it. The fusion reaction converts the missing mass into energy that allows the Sun to heat the Earth and permits the formation of life. The mass loss, *m*, during the fusion supplies an energy, *E*, according to $E = mc^2$. Every second, fusion reactions convert about 700 million metric tons of hydrogen into helium within the Sun's core, thereby releasing tremendous energy.

SEE ALSO Radioactivity (1896), Conservation of Energy (1843), Special Theory of Relativity (1905), Atomic Nucleus (1911), Einstein as Inspiration (1921), Energy from the Nucleus (1942), Stellar Nucleosynthesis (1946).

A USSR stamp from 1979, dedicated to Albert Einstein and $E = mc^2$.



1905

Photoelectric Effect • *Clifford A. Pickover*

Albert Einstein (1879–1955)

Of all of Albert Einstein's masterful achievements, including the Special Theory of Relativity and the General Theory of Relativity, the achievement for which he won the Nobel Prize, was his explanation of the workings of the photoelectric effect (PE), in which certain frequencies of light shined on a copper plate cause the plate to eject electrons. In particular, he suggested that packets of light (now called photons) could explain the PE. For example, it had been noted that high-frequency light, such as blue or ultraviolet light, could cause electrons to be ejected—but not low-frequency red light. Surprisingly, even intense red light did not lead to electron ejection. In fact, the energy of individual emitted electrons increases with the frequency (and, hence, the color) of the light.

How could the frequency of light be the key to the PE? Rather than light exerting its effect as a classical wave, Einstein suggested that the energy of light came in the form of packets, or *quanta*, and that this energy was equal to the light frequency multiplied by a constant (later called *Planck's constant*). If the photon was below a threshold frequency, it just did not have the energy to kick out an electron. As a very rough metaphor for low-energy red quanta, imagine the impossibility of chipping a fragment from a bowling ball by tossing peas at it. It just won't work, even if you toss lots of peas! Einstein's explanation for the energy of the photons seemed to account for many observations, such as for a given metal, there exists a certain minimum frequency of incident radiation below which no photoelectrons can be emitted. Today, numerous devices, such as solar cells, rely on conversion of light to electric current in order to generate power.

In 1969, American physicists suggested that one could actually account for the PE without the concept of photons; thus, the PE did not provide definitive *proof* of photon existence. However, studies of the statistical properties of the photons in the 1970s provided experimental verification of the manifestly quantum (nonclassical) nature of the electromagnetic field.

SEE ALSO Wave Nature of Light (1801), Atomic Theory (1808), Electron (1897), Special Theory of Relativity (1905), General Theory of Relativity (1915), Einstein as Inspiration (1921), Quantum Electrodynamics (1948).

Photograph through night-vision device. U.S. Army paratroopers train using infrared lasers and night-vision optics in Camp Ramadi, Iraq. Night-vision goggles make use of the ejection of photoelectrons due to the photoelectric effect to amplify the presence of individual photons.

1905

Special Theory of Relativity • *Clifford A. Pickover*

Albert Einstein (1879–1955)

Albert Einstein's Special Theory of Relativity (STR) is one of humankind's greatest intellectual triumphs. When Albert Einstein was only 26, he made use of one of the key foundations of STR—namely, that the speed of light in a vacuum is independent of the motion of the light source and the same for all observers, no matter how they are moving. This is in contrast to the speed of sound, which changes for an observer who moves, for example, with respect to the sound source. This property of light led Einstein to deduce the *relativity of simultaneity*: Two events occurring at the same time as measured by one observer sitting in a laboratory frame of reference occur at different times for an observer moving relative to this frame.

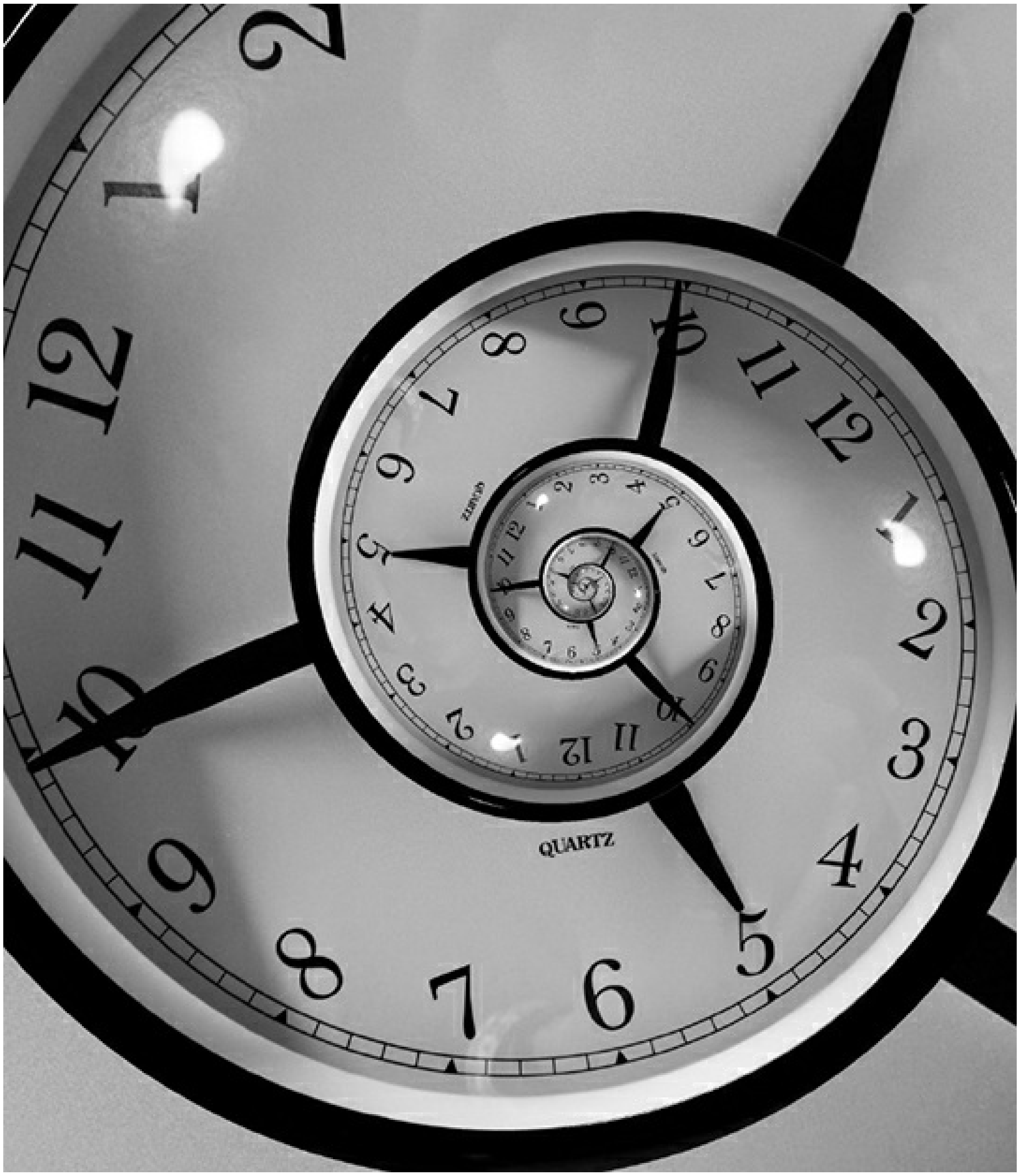
Because time is relative to the speed one is traveling at, there can never be a clock at the center of the Universe to which everyone can set their watches. Your entire life can be the blink of an eye to an alien who leaves the Earth traveling close to the speed of light and then returns an hour later to find that you have been dead for centuries. (The word "relativity" partly derives from the fact that the appearance of the world depends on our relative states of motion—the appearance is "relative.")

Although the strange consequences of STR have been understood for over a century, students still learn of them with a sense of awe and bewilderment. Nevertheless, from tiny subatomic particles to galaxies, STR appears to accurately describe nature.

To help understand another aspect of STR, imagine yourself in an airplane traveling at constant speed relative to the ground. This may be called the *moving frame of reference*. The principle of relativity makes us realize that without looking out the window, you cannot tell how fast you are moving. Because you cannot see the scenery moving by, for all you know, you could be in an airplane on the ground in a stationary frame of reference with respect to the ground.

SEE ALSO Michelson-Morley Experiment (1887), $E = mc^2$ (1905), General Theory of Relativity (1915), Einstein as Inspiration (1921), Dirac Equation (1928), Time Travel (1949).

There can never be a clock at the center of the Universe to which everyone can set their watches. Your entire life can be the blink of an eye to an alien who leaves earth traveling at high speed and then returns.


QUARTZ

1908

Internal Combustion Engine • *Marshall Brain*

The first widely adopted internal combustion engine was found in the Model T Ford starting in 1908. The Model T engine was based on the Otto cycle engine, also known as the four-stroke engine, patented in 1861 by Alphonse Beau de Rochas. An incredible amount of engineering went into making the Model T engine cheap, reliable, and long-lasting, given the materials and manufacturing processes available at the time. Over fifteen million Model Ts had been manufactured when production ended in 1927.

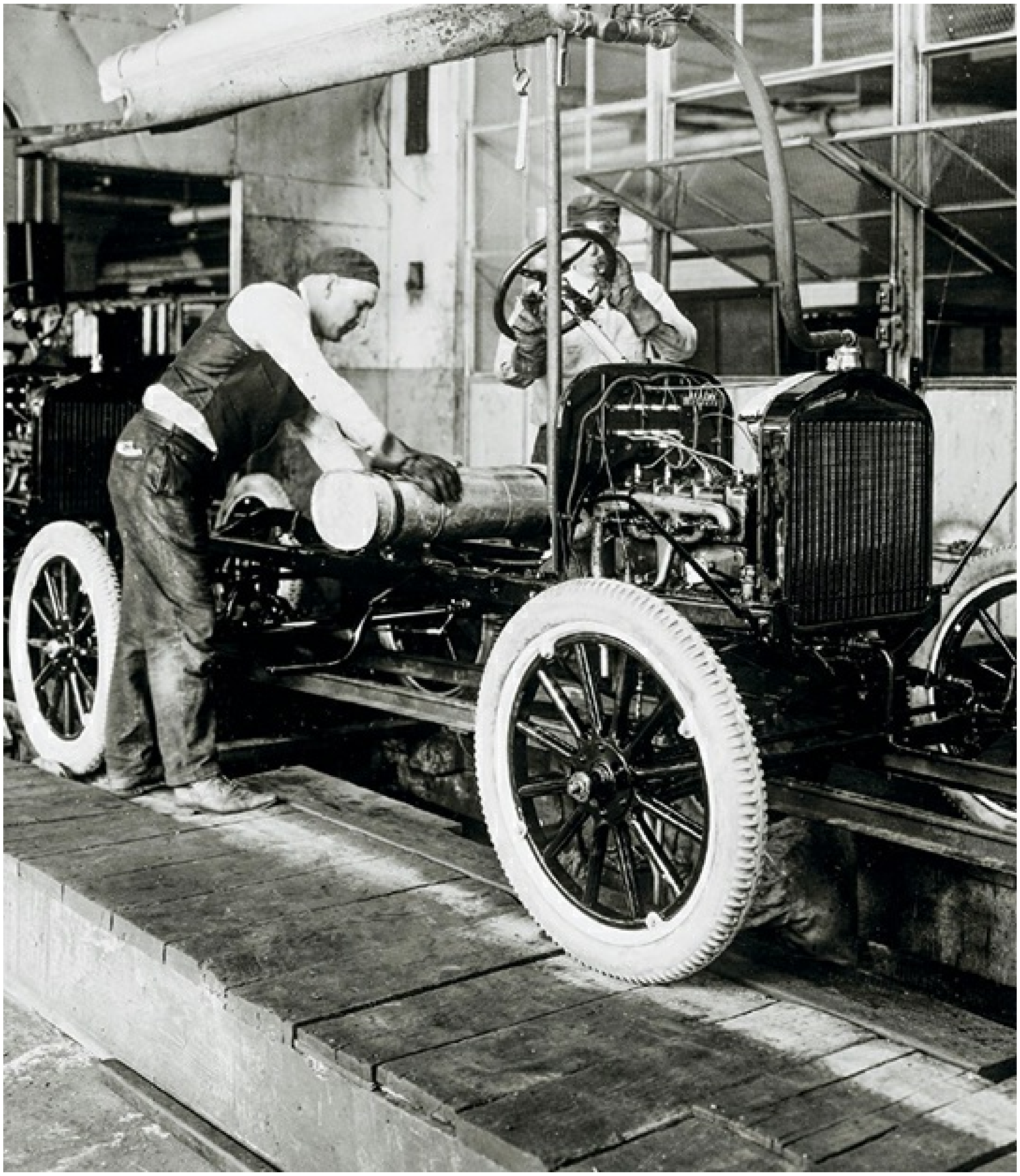
The engine contained a number of engineering marvels. Materials engineers improved on the Bessemer Process to create vanadium steel, which is so strong that some Model T engines still run today. Electrical engineers created the trembler coil ignition system that helped the engine run on gasoline, kerosene, or ethanol. Engineers also created the thermosiphon system, which moved water through the radiator without a water pump. But the real heroes were the manufacturing engineers, who made it possible to eventually produce two million cars per year with amazing efficiency, keeping prices low.

But if you compare the Model T engine with today’s engines, you can see that engineers since have been able to achieve a galaxy of improvements. The Model T engine had four cylinders displacing 2.9 liters, yet it produced only 20 horsepower. There are motorcycles today that produce 200 horsepower from one-liter engines. How is this possible? Engineers created overhead valve trains and high compression ratios to replace the flathead design on the Model T. They increased the redline and created fuel injection systems to replace carburetors. They designed much more powerful and precise ignition systems. They created tuned intake and exhaust systems.

Few technologies are in such widespread use and have been so highly refined without a reconceptualization. After over one hundred years of change, all of the core principles of the Model T engine—pistons, valves, spark plugs, water cooling, gasoline—are still in place. But each one has been fine-tuned and highly optimized by engineers to create the compact, reliable, high-power engines of today.

SEE ALSO High-Pressure Steam Engine (1800), Carnot Engine (1824), Wright Brothers' Airplane (1903).

Technician working on an internal combustion engine, possibly at Ford Motor Company, in 1949.



1910

Chlorination of Water • *Clifford A. Pickover*

Carl Rogers Darnall (1867–1941), William J. L. Lyster (1869–1947)

In 1997, *LIFE* magazine declared, “The filtration of drinking water plus the use of chlorine is probably the most significant public health advancement of the millennium.” Adding chlorine, a chemical element, to water is usually an effective treatment against bacteria, viruses, and amoebas, and has played a large role in the dramatic increase in life expectancy in developed countries during the 1900s. For example, in the United States, waterborne bacterial diseases such as typhoid and cholera became rare after drinking water was chlorinated. Because chlorine remains in the water supply after initial treatment, it continues to fight contamination from possible pipe leaks.

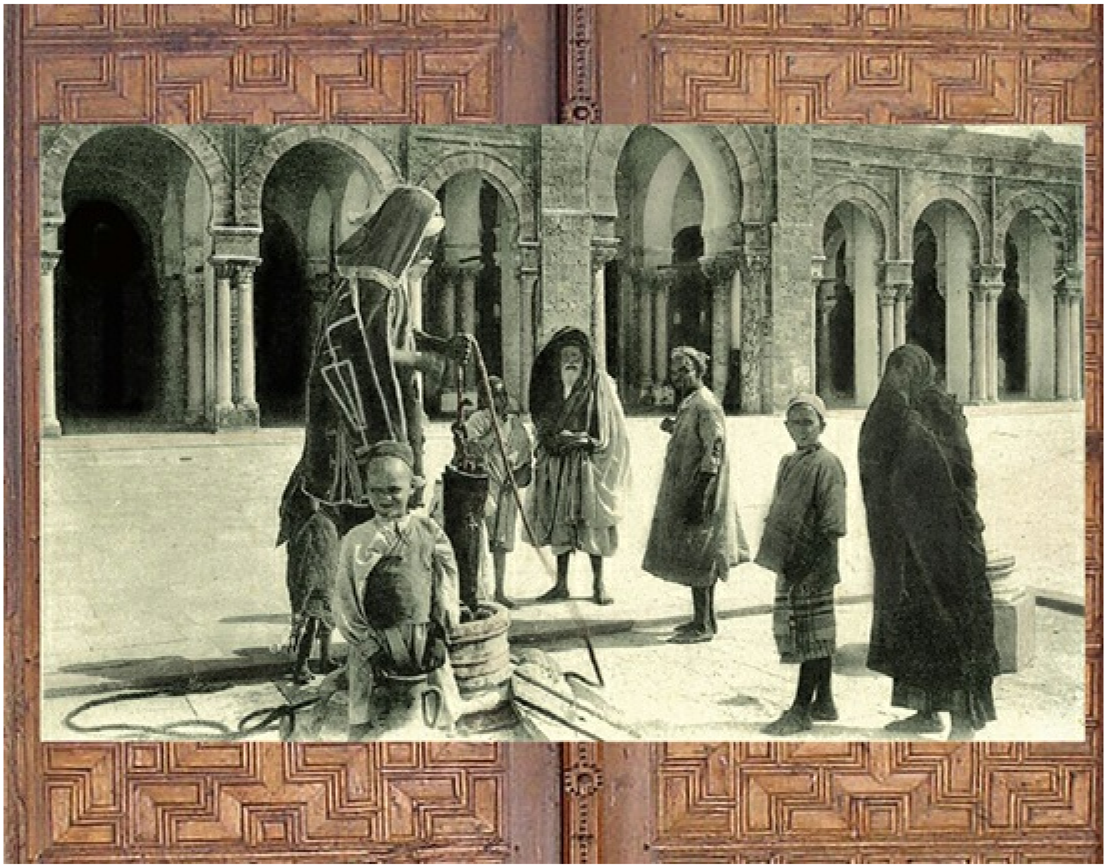
Chlorination was known to be an effective disinfectant in the 1800s, but water chlorination systems for public water supplies were not in continuous use until the early 1900s. Around 1903, the community in Middelkerke, Belgium, used chlorine gas for disinfection of drinking water, and in 1908 a water utility in Jersey City, New Jersey, used sodium hypochlorite for water chlorination. In 1910, Brigadier General Carl Rogers Darnall, a U.S. Army chemist and surgeon, used compressed liquefied chlorine gas to purify water for troops on the battlefield. The basic ideas in his invention of a mechanical liquid-chlorine purifier are now used throughout the developed world. Army scientist Major William Lyster subsequently invented the Lyster cloth bag, containing sodium hypochlorite and used to conveniently treat water by troops in the field.

The chlorine applied during water disinfection can react with organic compounds in the water to produce trihalomethanes and haloacetic acids, which have the potential to cause cancer. However, the risk of these compounds is low when compared with the risk of waterborne diseases. Alternatives to chlorination include disinfection with ozone, chloramine, and ultraviolet light.

According to spokespeople for the Darnall Army Medical Center, "It is safe to say that more lives have been saved and more sickness prevented by Darnall's contribution to sanitary water than by any other single achievement in medicine."

SEE ALSO Sewage Systems (c. 600 BCE) Germ Theory of Disease (1862), Antiseptics (1865).

LEFT: *Water well in a medieval village in Spain.* RIGHT: *A water well at the Great Mosque of Kairouan, Tunisia (postcard from 1900, overlaid on patterns from the door of the prayer hall). In modern times, wells are sometimes periodically cleaned with a chlorine solution to reduce bacterial levels.*



1910

Main Sequence • *Jim Bell*

Ejnar Hertzsprung (1873–1967), **Henry Norris Russell** (1877–1957)

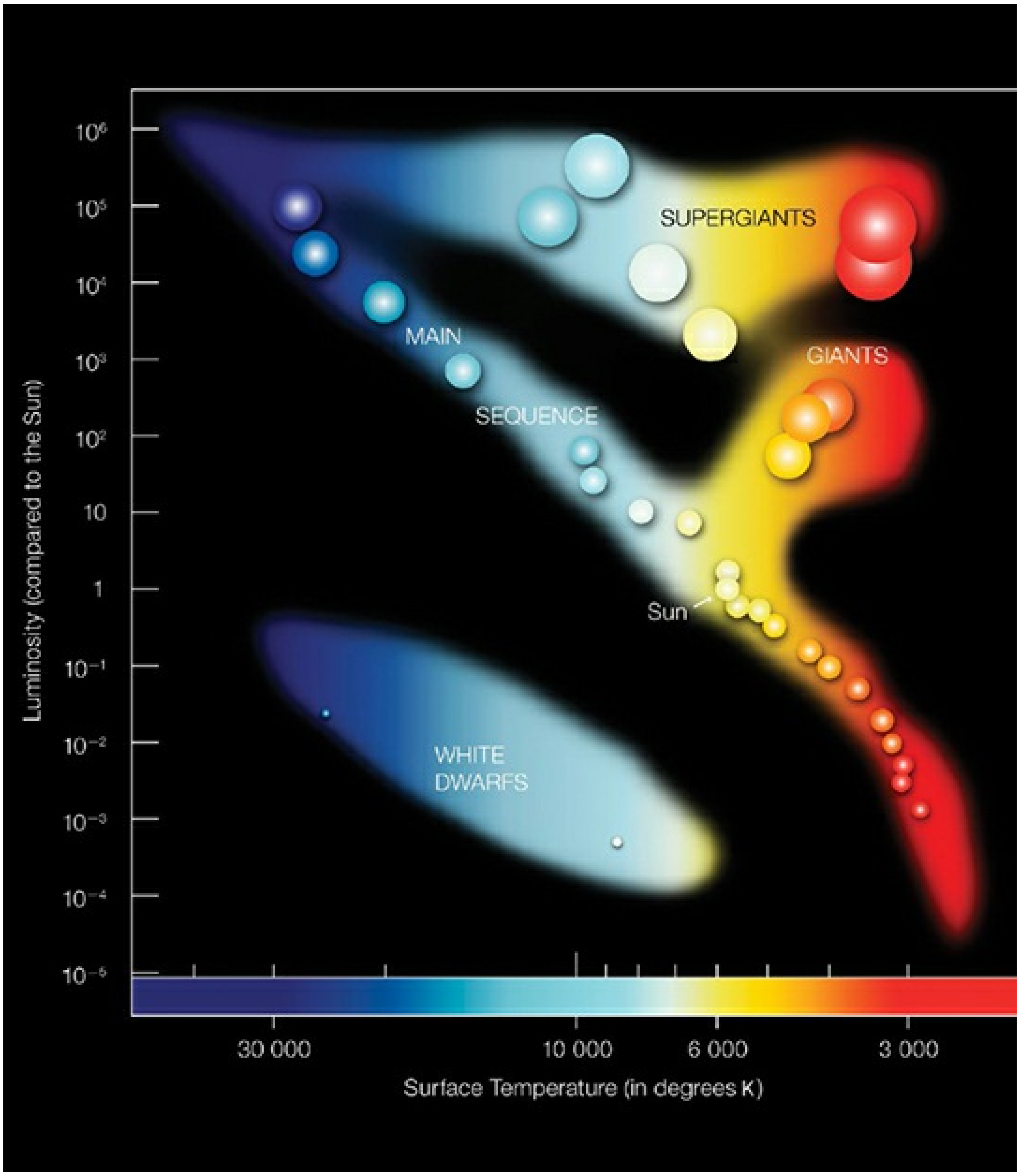
In the early part of the twentieth century, astronomers worldwide were characterizing and classifying enormous numbers of stars in terms of their colors and spectroscopic lines, expanding on the methods pioneered by Edward Pickering's Group at Harvard. Among the most important advances was the observation, noticed independently by the Danish astronomer Ejnar Hertzsprung and the American astronomer Henry Norris Russell, that when the spectral classes or temperatures of the stars were plotted against their actual brightness (that is, after their apparent brightness in the sky was corrected for their distance from us), most of the stars cluster in a broad sequence from upper left to lower right. Hertzsprung coined the term "main sequence" to describe this prominent trend among the stars. Such plots began being used around 1910 and are called Hertzsprung-Russell (H-R) diagrams.

Over the next few decades astronomers began to understand that the main sequence was more than just a random clustering—it represents an evolutionary pathway for tracking the age and eventual fate of the stars. Most stars are born when their central pressures and temperatures are high enough for the nuclear fusion of hydrogen atoms into helium. During this hydrogen-fusing phase of its lifetime, a normal star will plot on the main sequence at a position that depends on its mass, with luminous stars a few to ten times the mass of the Sun (blue giants) on the upper left end of the plot and dim stars from about one-tenth to one-half the Sun's mass (red dwarfs) on the lower right. As stars age and run out of hydrogen fuel, they diverge off the main sequence and eventually “die” in characteristic (and often spectacular) ways that again depend on their mass.

As the details of stellar interiors later became understood by astrophysicists such as Arthur Eddington and Hans Bethe, it became possible to predict how stars of specific masses would live and die. Our Sun turns out to be an average mass, middle-aged, main sequence star that appears destined, in about 5 billion more years, to bloat up into a red giant, expel its outer layers into a planetary nebula, and then fade away as a white dwarf.

SEE ALSO Black Holes (1783), Pauli Exclusion Principle (1925), Neutron (1932).

Plots of the intrinsic luminosity of stars (on the y axis, normalized so the Sun’s luminosity = 1) versus their color—or equivalently, their temperature (on the x axis)—reveal a prominent diagonal band of stars known as the main sequence, bracketed by brighter blue and red giants and dimmer white dwarfs.



10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Luminosity (compared to the Sun)
SUPERGIANTS
MAIN
SEQUENCE
GIANTS
Sun
WHITE
DWARFS
30 000
10 000
6 000
3 000
Surface Temperature (in degrees K)

1911

Atomic Nucleus • *Clifford A. Pickover*

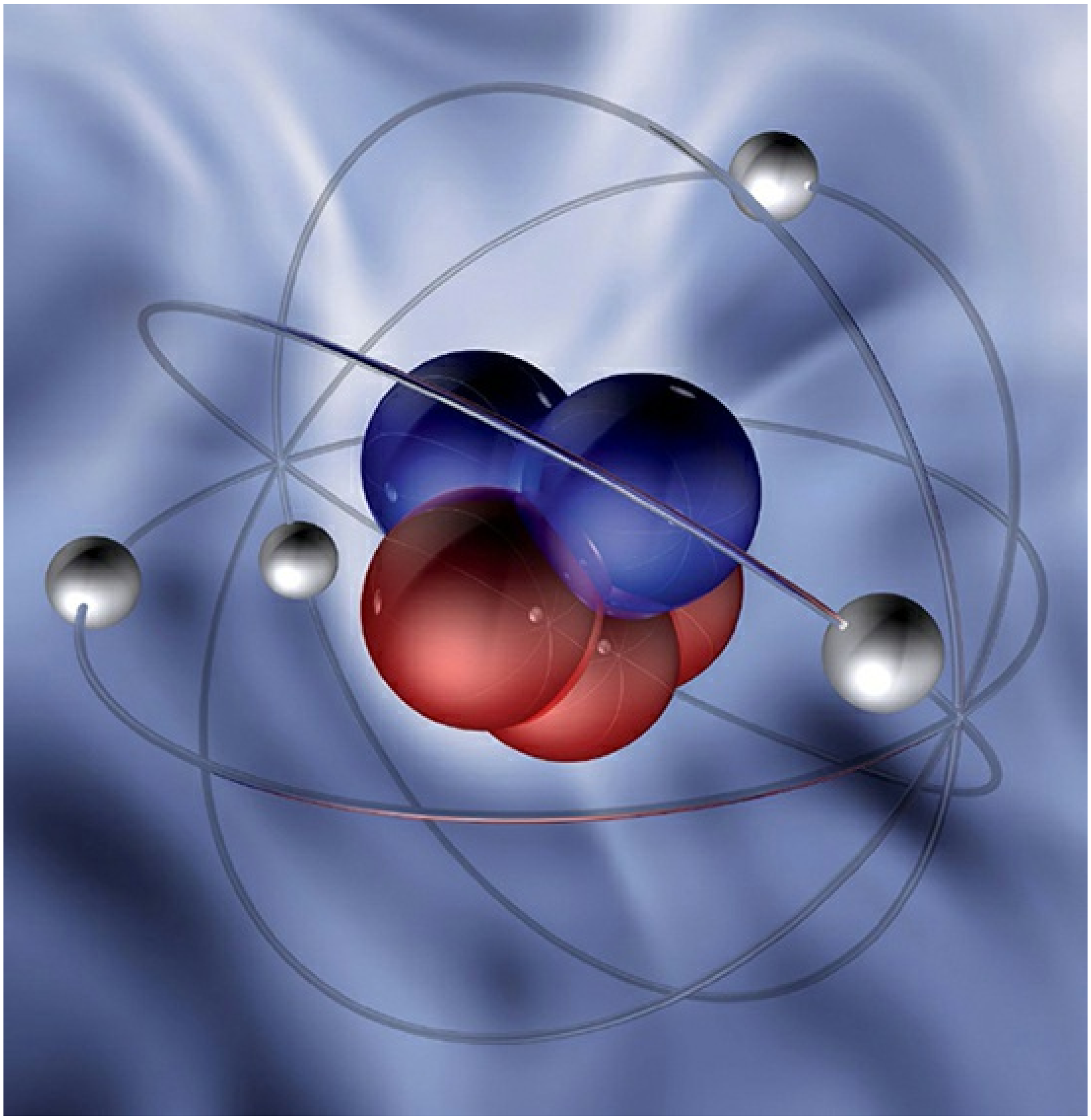
Ernest Rutherford (1871–1937)

Today, we know that the atomic nucleus, which consists of protons and neutrons, is the very dense region at the center of an atom. However, in the first decade of the 1900s, scientists were unaware of the nucleus and thought of the atom as a diffuse web of positively charged material, in which negatively charged electrons were embedded like cherries in a cake. This model was utterly destroyed when Ernest Rutherford and his colleagues discovered the nucleus after they fired a beam of alpha particles at a thin sheet of gold foil. Most of the alpha particles (which we know today as helium nuclei) went through the foil, but a few bounced straight back. Rutherford said later that this was "quite the most incredible event that has ever happened to me. . . . It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you."

The cherry-cake model of the atom, which was a metaphor for a somewhat uniform spread of density across the gold foil, could never account for this behavior. Scientists would have observed the alpha particles slow down, perhaps, like a bullet being fired through water. They did not expect the atom to have a "hard center" like a pit in a peach. In 1911, Rutherford announced a model with which we are familiar today: an atom consisting of a positively charged nucleus encircled by electrons. Given the frequency of collisions with the nucleus, Rutherford could approximate the size of the nucleus with respect to the size of the atom. Author John Gribbin writes that the nucleus has "one hundred-thousandth of the diameter of the whole atom, equivalent to the size of a pinhead compared with the dome of St. Paul's cathedral in London. . . . And since everything on Earth is made of atoms, that means that your own body, and the chair you sit on, are each made up of a million billion times more empty space than ‘solid matter.’”

SEE ALSO Atomic Theory (1808), Electron (1897), $E = mc^2$ (1905), Bohr Atom (1913), Neutron (1932), Nuclear Magnetic Resonance (1938), Energy from the Nucleus (1942), Stellar Nucleosynthesis (1946).

Artistic rendition of a classical model of the atom with its central nucleus. Only some of the nucleons (protons and neutrons) and electrons are seen in this view. In an actual atom, the diameter of the nucleus is very much smaller than the diameter of the entire atom. Modern depictions of the surrounding electrons often depict them as clouds that represent probability densities.



1911

Superconductivity • *Clifford A. Pickover*

Heike Kamerlingh Onnes (1853–1926), **John Bardeen** (1908–1991), **Karl Alexander Müller** (b. 1927), **Leon N. Cooper** (b. 1930), **John Robert Schrieffer** (b. 1931), **Johannes Georg Bednorz** (b. 1950)

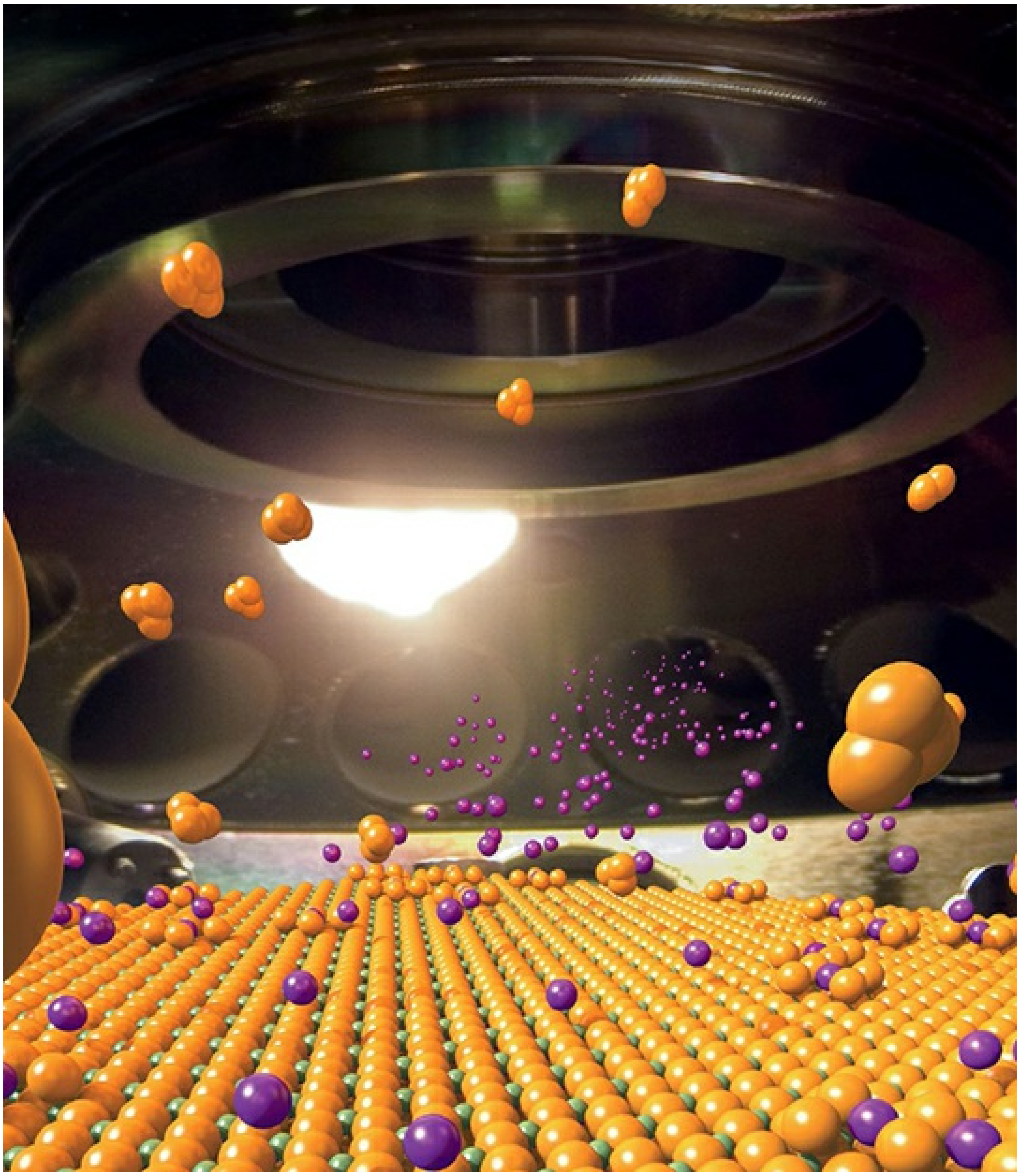
"At very low temperatures," writes science-journalist Joanne Baker, "some metals and alloys conduct electricity without any resistance. The current in these superconductors can flow for billions of years without losing any energy. As electrons become coupled and all move together, avoiding the collisions that cause electrical resistance, they approach a state of perpetual motion."

In fact, many metals exist for which the resistivity is zero when they are cooled below a critical temperature. This phenomenon, called superconductivity, was discovered in 1911 by Dutch physicist Heike Onnes, who observed that when he cooled a sample of mercury to 4.2 degrees above absolute zero (−452.1°F), its electrical resistance plunged to zero. In principle, this means that an electrical current can flow around a loop of superconducting wire forever, with no external power source. In 1957, American physicists John Bardeen, Leon Cooper, and Robert Schrieffer determined how electrons could form pairs and appear to ignore the metal around them: Consider a metal window screen as a metaphor for the arrangement of positively charged atomic nuclei in a metal lattice. Next, imagine a negatively charged electron zipping between the atoms, creating a distortion by pulling on them. This distortion attracts a second electron to follow the first; they travel together in a pair, and encounter less resistance overall.

In 1986, Georg Bednorz and Alex Müller discovered a material that operated at the higher temperature of roughly −396°F (35 kelvins), and in 1987 a different material was found to superconduct at −297°F (90 kelvins). If a superconductor is discovered that operates at room temperature, it could be used to save vast amounts of energy and to create a high-performance electrical power transmission system. Superconductors also expel all applied magnetic fields, which allows engineers to build magnetically levitated trains. Superconductivity is also used to create powerful electromagnets in MRI (magnetic-resonance imaging) scanners in hospitals.

SEE ALSO Battery (1800), Electron (1897), Nuclear Magnetic Resonance (1938).

In 2008, physicists at the U.S. Department of Energy's Brookhaven National Laboratory discovered interface high-temperature superconductivity in bilayer films of two cuprate materials—with potential for creating higher-efficiency electronic devices. In this artistic rendition, these thin films are built layer by layer.



1912

Bragg's Law of Crystal Diffraction •

Clifford A. Pickover

William Henry Bragg (1862–1942), **William Lawrence Bragg** (1890–1971)

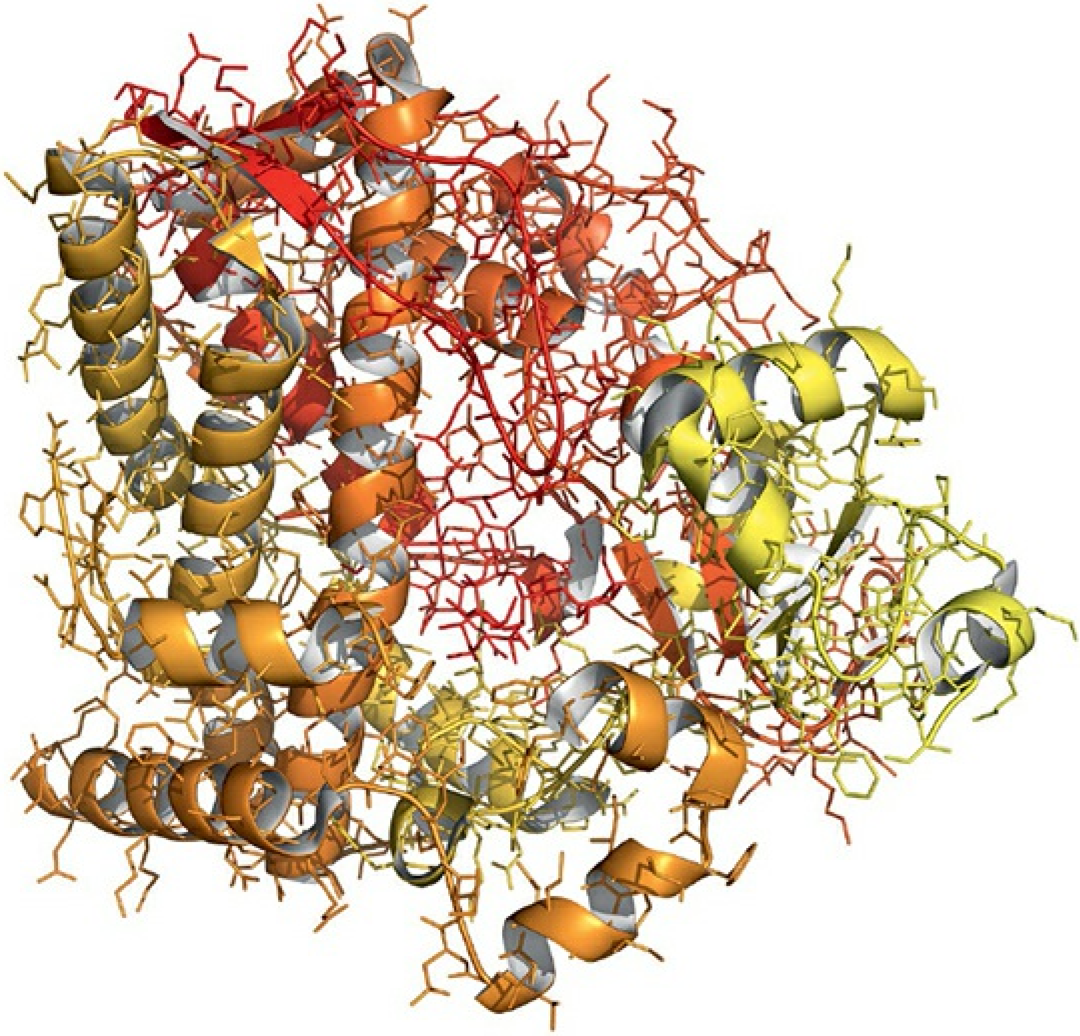
"I was captured for life by chemistry and by crystals," wrote X-ray crystallographer Dorothy Crowfoot Hodgkin whose research depended on Bragg's Law. Discovered by the English physicists Sir W. H. Bragg and his son Sir W. L. Bragg in 1912, Bragg's Law explains the results of experiments involving the diffraction of electromagnetic waves from crystal surfaces. Bragg's Law provides a powerful tool for studying crystal structure. For example, when X-rays are aimed at a crystal surface, they interact with atoms in the crystal, causing the atoms to re-radiate waves that may interfere with one another. The interference is constructive (reinforcing) for integer values of n according to Bragg's Law: $n\lambda = 2d \sin(\theta)$. Here, λ is the wavelength of the incident electromagnetic waves (e.g. X-rays); d is the spacing between the planes in the atomic lattice of the crystal; and θ is the angle between the incident ray and the scattering planes.

For example, X-rays travel down through crystal layers, reflect, and travel back over the same distance before leaving the surface. The distance traveled depends on the separation of the layers and the angle at which the X-ray entered the material. For maximum intensity of reflected waves, the waves must stay in phase to produce the constructive interferences. Two waves stay in phase, after both are reflected, when n is a whole number. For example, when $n = 1$, we have a "first order" reflection. For $n = 2$, we have a "second order" reflection. If only two rows were involved in the diffraction, as the value of θ changes, the transition from constructive to destructive interference is gradual. However, if interference from many rows occurs, then the constructive interference peaks become sharp, with mostly destructive interference occurring in between the peaks.

Bragg's Law can be used for calculating the spacing between atomic planes of crystals and for measuring the radiation's wavelength. The observations of X-ray wave interference in crystals, commonly known as X-ray diffraction, provided direct evidence for the periodic atomic structure of crystals that was postulated for several centuries.

SEE ALSO Wave Nature of Light (1801), X-rays (1895), Hologram (1947).

LEFT: *Copper sulfate. In 1912, physicist Max von Laue used X-rays to record a diffraction pattern from a copper sulfate crystal, which revealed many well-defined spots. Prior to X-ray experiments, the spacing between atomic lattice planes in crystals was not accurately known.* RIGHT: *Bragg's Law eventually led to studies involving the X-ray scattering from crystal structures of large molecules such as enzymes. Shown here is a model of the human cytochrome P450 liver enzyme, which plays a role in drug detoxification.*



1912

Continental Drift • *Michael C. Gerald with Gloria E. Gerald*

Alexander von Humboldt (1769–1859), **Alfred Wegener** (1880–1930)

Even casual inspection of a map of the Southern Hemisphere suggests that the coastlines of eastern South America and western Africa fit together like the pieces of a jigsaw puzzle. This same thought occurred to the naturalist-explorer Alexander von Humboldt who, during the early 1800s, found similarities between animal and plant fossils in South America and western Africa, and common elements between the mountain ranges in Argentina and South Africa. Subsequent explorers saw similarities between fossils in India and Australia.

In 1912, the German geophysicist-meteorologist and polar explorer Alfred Wegener went a step further and proposed that the present continents were once fused into a single landmass, which he called *Pangaea* (“All-Lands”). Expanding upon this theory in his 1915 book, *The Origin of Continents and Oceans*, Wegener described how Pangaea subsequently split into two supercontinents, Laurasia (corresponding to the present-day Northern Hemisphere) and Gondwanaland, also called Gondwana (Southern Hemisphere)—an event now thought to have occurred 180 to 200 million years ago. Wegener could not provide an explanation for continental drift, and his concept was roundly rejected until after his death in 1930 from heart failure during an expedition to Greenland. The occurrence of continental drift was finally accepted in the 1960s, when the concept of *plate tectonics*—involving plates that are in constant motion relative to each other, sliding under other plates and pulling apart—was established.

Long before continental drift was acknowledged by the scientific community, naturalists were finding ancient fossils of the same or similar plants and animals in continents thousands of miles apart and separated by oceans. Fossil remains of the tropical fern *Glossopteris* were found in South America, Africa, India, and Australia, while those of the family *Kannemeyrid*, a mammal-like reptile, were uncovered in Africa, Asia, and South America. By contrast, some living plants and animals on different continents are very different from one another. For example, all the native mammals in Australia are marsupials and not placental mammals, which suggests that Australia split off from Gondwanaland before placental mammals evolved.

SEE ALSO Darwin and the Voyages of the *Beagle* (1831), Fossil Record and Evolution (1836), Darwin's Theory of Natural Section (1859).

According to the theory of continental drift, a single giant landmass, Pangaea, split into the two supercontinents, Laurasia (Northern Hemisphere) and Gondwana (Southern Hemisphere).

PANGAEA
200 million years ago

LAURASIA & GONDWANA
120 million years ago

1913

Bohr Atom • *Clifford A. Pickover*

Niels Henrik David Bohr (1885–1962)

"Somebody once said about the Greek language that Greek flies in the writings of Homer," writes physicist Amit Goswami. "The quantum idea started flying with the work of Danish physicist Niels Bohr published in the year 1913." Bohr knew that negatively charged electrons are easily removed from atoms and that the positively charged nucleus occupied the central portion of the atom. In the Bohr model of the atom, the nucleus was considered to be like our central Sun, with electrons orbiting like planets.

Such a simple model was bound to have problems. For example, an electron orbiting a nucleus would be expected to emit electromagnetic radiation. As the electron lost energy, it should decay and fall into the nucleus. In order to avoid atomic collapse as well as to explain various aspects of the emission spectra of the hydrogen atom, Bohr postulated that the electrons could not be in orbits with an arbitrary distance from the nucleus. Rather, they were restricted to particular allowed orbits or shells. Just like climbing or descending a ladder, the electron could jump to a higher rung, or shell, when the electron received an energy boost, or it could fall to a lower shell, *if* one existed. This hopping between shells takes place only when a photon of the particular energy is absorbed or emitted from the atom. Today we know that the model has many shortcomings and does not work for larger atoms, and it violates the Heisenberg Uncertainty Principle because the model employs electrons with a definite mass and velocity in orbits with definite radii.

Physicist James Trefil writes, "Today, instead of thinking of electrons as microscopic planets circling a nucleus, we now see them as probability waves sloshing around the orbits like water in some kind of doughnut-shaped tidal pool governed by Schrödinger’s Equation. . . . Nevertheless, the basic picture of the modern quantum mechanical atoms was painted back in 1913, when Niels Bohr had his great insight.” *Matrix mechanics*—the first complete definition of quantum mechanics—later replaced the Bohr Model and better described the observed transitions in energy states of atoms.

SEE ALSO Electron (1897), Atomic Nucleus (1911), Pauli Exclusion Principle (1925), Schrödinger’s Wave Equation (1926), Heisenberg Uncertainty Principle (1927).

These amphitheater seats in Ohrid, Macedonia, are a metaphor for Bohr’s electron orbits. According to Bohr, electrons could not be in orbits with an arbitrary distance from the nucleus; rather, electrons were restricted to particular allowed shells associated with discrete energy levels.

1915

General Theory of Relativity • *Clifford A. Pickover*

Albert Einstein (1879–1955)

Albert Einstein once wrote that "all attempts to obtain a deeper knowledge of the foundations of physics seem doomed to me unless the basic concepts are in accordance with general relativity from the beginning." In 1915, ten years after Einstein proclaimed his *Special* Theory of Relativity (which suggested that distance and time are not absolute and that one's measurements of the ticking rate of a clock depend on one's motion with respect to the clock), Einstein gave us an early form of his *General* Theory of Relativity (GTR), which explained gravity from a new perspective. In particular, Einstein suggested that gravity is not really a force like other forces, but results from the curvature of space-time caused by masses in space-time. Although we now know that GTR does a better job at describing motions in high gravitational fields than Newtonian mechanics (such as the orbit of Mercury about the Sun), Newtonian mechanics still is useful in describing the world of ordinary experience.

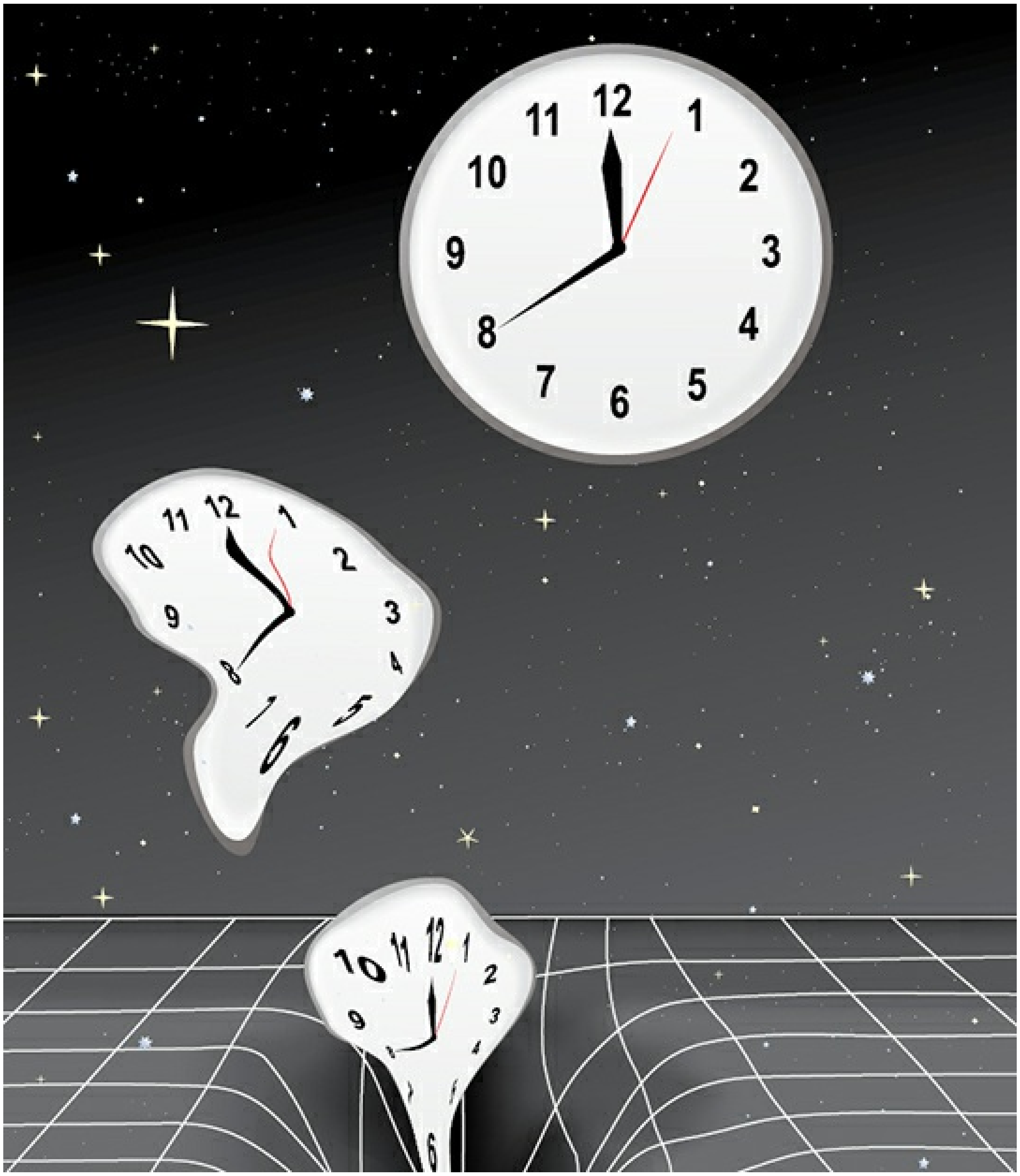
To better understand GTR, consider that wherever a mass exists in space, it warps space. Imagine a bowling ball sinking into a rubber sheet. This is a convenient way to visualize what stars do to the fabric of the universe. If you were to place a marble into the depression formed by the stretched rubber sheet, and give the marble a sideways push, it would orbit the bowling ball for a while, like a planet orbiting the Sun. The warping of the rubber sheet by the bowling ball is a metaphor for a star warping space.

GTR can be used to understand how gravity warps and slows time. In a number of circumstances, GTR also appears to permit time travel.

Einstein additionally suggested that gravitational effects move at the speed of light. Thus, if the Sun were suddenly plucked from the Solar System, the Earth would not leave its orbit about the Sun until about eight minutes later, the time required for light to travel from the Sun to the Earth. Many physicists today believe that gravitation must be quantized and take the form of particles called gravitons, just as light takes the form of photons, which are tiny quantum packets of electromagnetism.

SEE ALSO Newton's Laws of Motion and Gravitation (1687), Black Holes (1783), Special Theory of Relativity (1905), Noether's *Idealtheorie* (1921), Einstein as Inspiration (1921), Time Travel (1949), Gravitational Waves (2016).

Einstein suggested that gravity results from the curvature of space-time caused by masses in space-time. Gravity distorts both time and space.



1919

String Theory • *Clifford A. Pickover*

Theodor Franz Eduard Kaluza (1885–1954), **John Henry Schwarz** (b. 1941), **Michael Boris Green** (b. 1946)

“The mathematics involved in string theory . . . ,” writes mathematician Michael Atiyah, “in subtlety and sophistication . . . vastly exceeds previous uses of mathematics in physical theories. String theory has led to a whole host of amazing results in mathematics in areas that seem far removed from physics. To many this indicates that string theory must be on the right track. . . .” Physicist Edward Witten writes, “String theory is twenty-first century physics that fell accidentally into the twentieth century.”

Various modern theories of “hyperspace” suggest that dimensions exist beyond the commonly accepted dimensions of space and time. For example, the Kaluza-Klein theory of 1919 made use of higher spatial dimensions in an attempt to explain electromagnetism and gravitation. Among the most recent formulations of these kinds of concepts is superstring theory, which predicts a universe of ten or eleven dimensions—three dimensions of space, one dimension of time, and six or seven more spatial dimensions. In many theories of hyperspace, the laws of nature become simpler and more elegant when expressed with these several extra spatial dimensions.

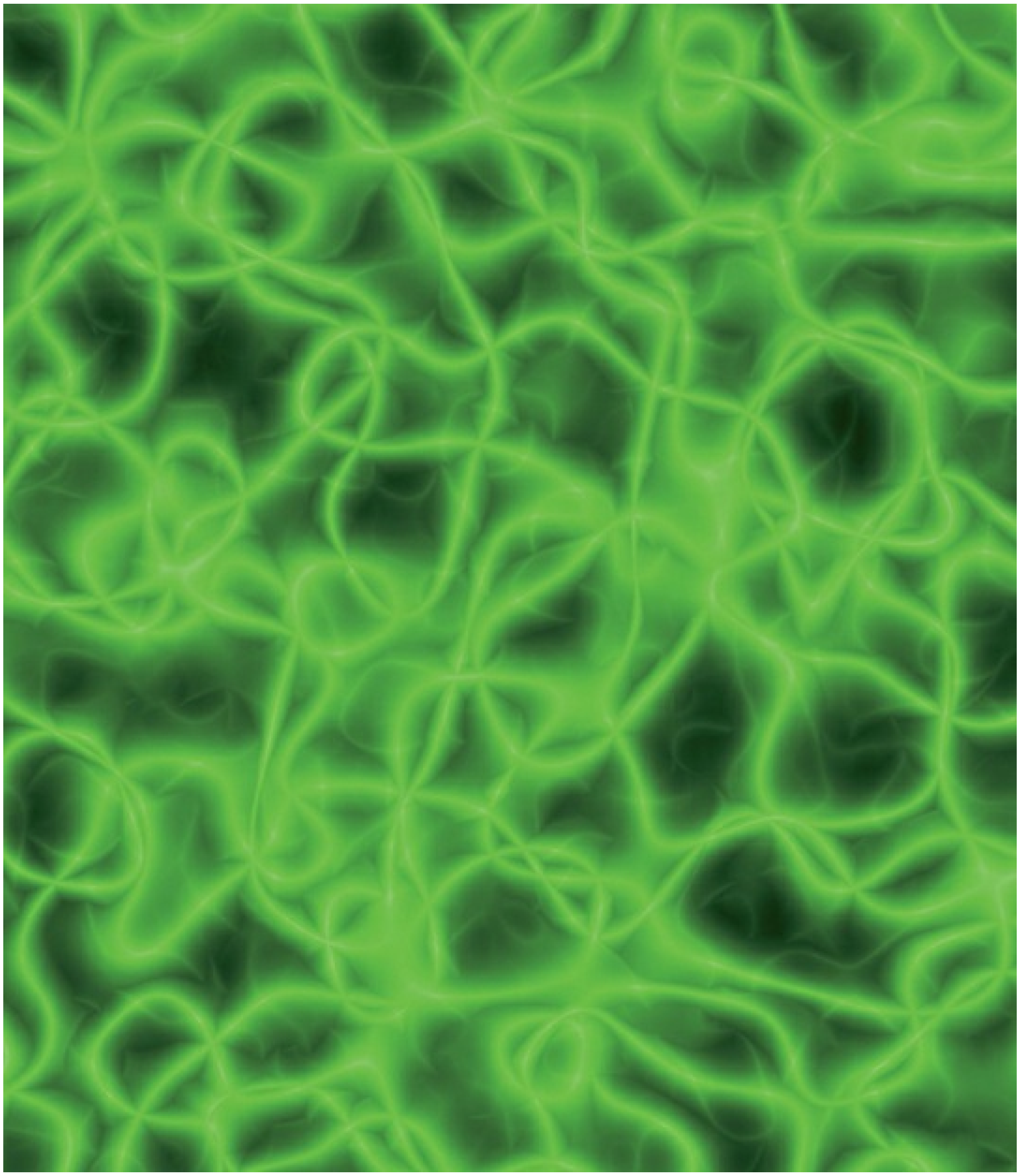
In string theory, some of the most basic particles, like quarks and electrons, can be modeled by inconceivably tiny, essentially one-dimensional entities called strings. Although strings may seem to be mathematical abstractions, remember that atoms were once regarded as “unreal” mathematical abstractions that eventually became observables. However, strings are so tiny that there is no current way to directly observe them.

In some string theories, the loops of string move about in ordinary 3-space, but they also vibrate in higher spatial dimensions. As a simple metaphor, think of a vibrating guitar string whose “notes” correspond to different particles such as quarks and electrons or the hypothetical graviton, which may convey the force of gravity.

String theorists claim that a variety of higher spatial dimensions are “compactified”—tightly curled up (in structures known as Calabi-Yau spaces) so that the extra dimensions are essentially invisible. In1984, Michael Green and John H. Schwarz made additional breakthroughs in string theory.

SEE ALSO Standard Model (1961), Theory of Everything (1984), Large Hadron Collider (2009).

In string theory, the vibrational pattern of the string determines what kind of particle the string is. For a metaphor, consider a violin. Pluck the A string and an electron is formed. Pluck the E string and you create a quark.



1920

Hydrogen Bonding • *Derek B. Lowe*

Worth Huff Rodebush (1887–1959), **Wendell Mitchell Latimer** (1893–1955), **Maurice Loyal Huggins** (1897–1981)

Hydrogen bonds are the secret adhesive of the living world. They hold together the strands of DNA, help to determine the shapes of proteins, and occur in every kind of carbohydrate molecule. The active sites of receptors and enzymes, for example, almost invariably feature key hydrogen bonds in the protein's own structure and with the substrate molecules that bind there.

American chemist Maurice Loyal Huggins was the first to suggest the concept of hydrogen bonds, and his work inspired his colleagues Wendell Mitchell Latimer and Worth Huff Rodebush to publish a 1920 paper that used hydrogen bonds to explain properties of certain liquids. Almost one hundred years of work since then have still not revealed all their secrets, though.

So what's a hydrogen bond? That's not such an easy question to answer. Even the best minds (such as American chemist Linus Pauling) have found plenty to occupy them here. Hydrogen bonding is partly just the attraction between a positively charged hydrogen atom and a negatively charged atom, such as nitrogen or oxygen, on a nearby molecule. These don't have to be full charges. Oxygen and nitrogen atoms usually have extra electron density, making them clumps of partial negative charge. But this isn't just an ionic bond, because hydrogen bonds are directional—if they're not pointed in the right way, the attraction mostly disappears. It's like a ghostly form of a standard single bond, and it's strongest when the hydrogen itself is attached to an electron-rich atom like oxygen as well. Such oxygen-hydrogen and nitrogen-hydrogen compounds are found over a huge range of chemistry, and they're especially crucial in the behavior of many biomolecules.

Water is the best example, with two hydrogen atoms attached to a single oxygen. Water molecules are very good hydrogen bond donors and acceptors at the same time, which is what makes it such a weird substance. It has a much higher boiling point than such a tiny molecule should, and it freezes into a hydrogen-bonded crystal lattice that's actually less dense than the liquid. (Most liquids don't have ice that floats.)

SEE ALSO Periodic Table (1869), Electron (1897), DNA Structure (1953).

Hydrogen bonding is essential to the properties of water, which are essential to life on Earth.

1920

Radio Station • *Marshall Brain*

If we could get in our time machine, go back to 1912, and stand on the deck of the sinking *Titanic*, there is something we would see overhead that marked the beginning of a new era in communication. The *Titanic* had two masts, one at either end of the ship, and a long wire stretching between them. This was the antenna for a 5,000-watt spark-gap radio, and the *Titanic* was using it to send out Morse code distress signals.

The *Titanic* put radio on the map. Because of that disaster, the Radio Act of 1912 required ships to monitor for distress calls 24 hours a day and set up a system for the US government to license radio stations.

By 1920, the first AM radio station was broadcasting in the United States: KDKA in Pittsburgh, PA. What had happened between 1912 and 1920 was the mass production of vacuum tubes, accelerated by World War I. Vacuum tubes gave electrical engineers the ability to create amplifiers for radio transmitters and receivers. Once engineers created the equipment, radio exploded in popularity. Everyone had to have a radio. By 1922 there were more than a million radio receivers in the US. Hundreds of organizations—newspapers, colleges, department stores, and individuals—had created radio stations. The Golden Age of Radio was born.

NBC started in 1926 and CBS started in 1927. Government regulation changed to make the advertising model possible in radio. With a revenue stream in place, there was a good reason for broadcasters to expand and plenty of money to pay for content.

This whole story is fascinating. The war led to tubes, which led to radios. The result was an entirely new way of thinking—instantaneous, electronic, free mass media to millions of people through nationwide networks funded by advertising. None of that existed in 1920. By 1930 nearly half of United States homes had radios. With the Great Depression starting, radio provided an inexpensive form of news and entertainment. Electrical engineering had created a massive societal change.

SEE ALSO Telegraph System (1837), Fiber Optics (1841), Telephone (1876), ARPANET (1969).

Turning on an early model radio. During the 1920s, amplifying vacuum tubes led to advancements in radio transmitters and receivers.

1921

Noether's *Idealtheorie* • *Clifford A. Pickover*

Amalie Emmy Noether (1882–1935)

Despite the horrible prejudice they faced, several women have fought against the establishment and persevered in mathematics. German mathematician Emmy Noether was described by Albert Einstein as "the most significant creative mathematical genius thus far produced since the higher education of women began."

In 1915, while at the University of Göttingen, Germany, Noether's first significant mathematical breakthrough was in theoretical physics. In particular, Noether's theorem dealt with symmetry relationships in physics and their relationship to conservation laws. This and related work was an aid to Einstein when he developed his general theory of relativity, which focused on the nature of gravity, space, and time.

After Noether had received her Ph.D., she attempted to teach at Göttingen, but her opponents said that men could not expect to learn "at the feet of a woman." Her colleague David Hilbert replied to her detractors, "I do not see that the sex of the candidate is against her admission as a privatdozent [licensed lecturer]. After all, the university senate is not a bathhouse."

Noether is also known for her contributions to noncommutative algebras, where the order in which terms are multiplied affects the results. She is most famous for her study of "chain conditions on ideals of rings," and, in 1921, Noether published *Idealtheorie in Ringbereichen*, which is of major importance in the development of modern abstract algebra. This area of mathematics examines the general properties of operations and often unifies logic and number theory with applied mathematics. Alas, in 1933, her mathematical achievements were utterly dismissed when the Nazis terminated her from the University of Göttingen because she was Jewish.

She fled Germany and joined the faculty at Bryn Mawr College in Pennsylvania. According to journalist Siobhan Roberts, Noether "made weekly trips to lecture at Princeton's institute, and to visit her friends Einstein and Herman Weyl." Her influence was far and wide, and many of her ideas appeared in papers written by students and colleagues.

SEE ALSO Hilbert's 23 Problems (1900), General Theory of Relativity (1915), Einstein as Inspiration (1921).

Amalie Emmy Noether, author of Idealtheorie in Ringbereichen (Theory of Ideals in Ring Domains), which was of major importance in the development of modern abstract algebra. Noether also developed some of the mathematics of general relativity but often toiled without pay.

1921

Einstein as Inspiration • *Clifford A. Pickover*

Albert Einstein (1879–1955)

Nobel-prize winner Albert Einstein is recognized as one of the greatest physicists of all time and the most important scientist of the twentieth century. He proposed the Special and General Theories of Relativity, which revolutionized our understanding of space and time. He also made major contributions to the science of quantum mechanics, statistical mechanics, and cosmology.

"Physics has come to dwell at such a deep remove from everyday experiences," writes Thomas Levenson, author of *Einstein in Berlin*, "that it's hard to say whether most of us would be able to recognize an Einstein-like accomplishment should it occur [today]. When Einstein first came to New York in 1921, thousands lined the street for a motorcade. . . . Try to imagine any theoretician today getting such a response. It's impossible. The emotional connections between the physicist's conception of reality and the popular imagination has weakened greatly since Einstein."

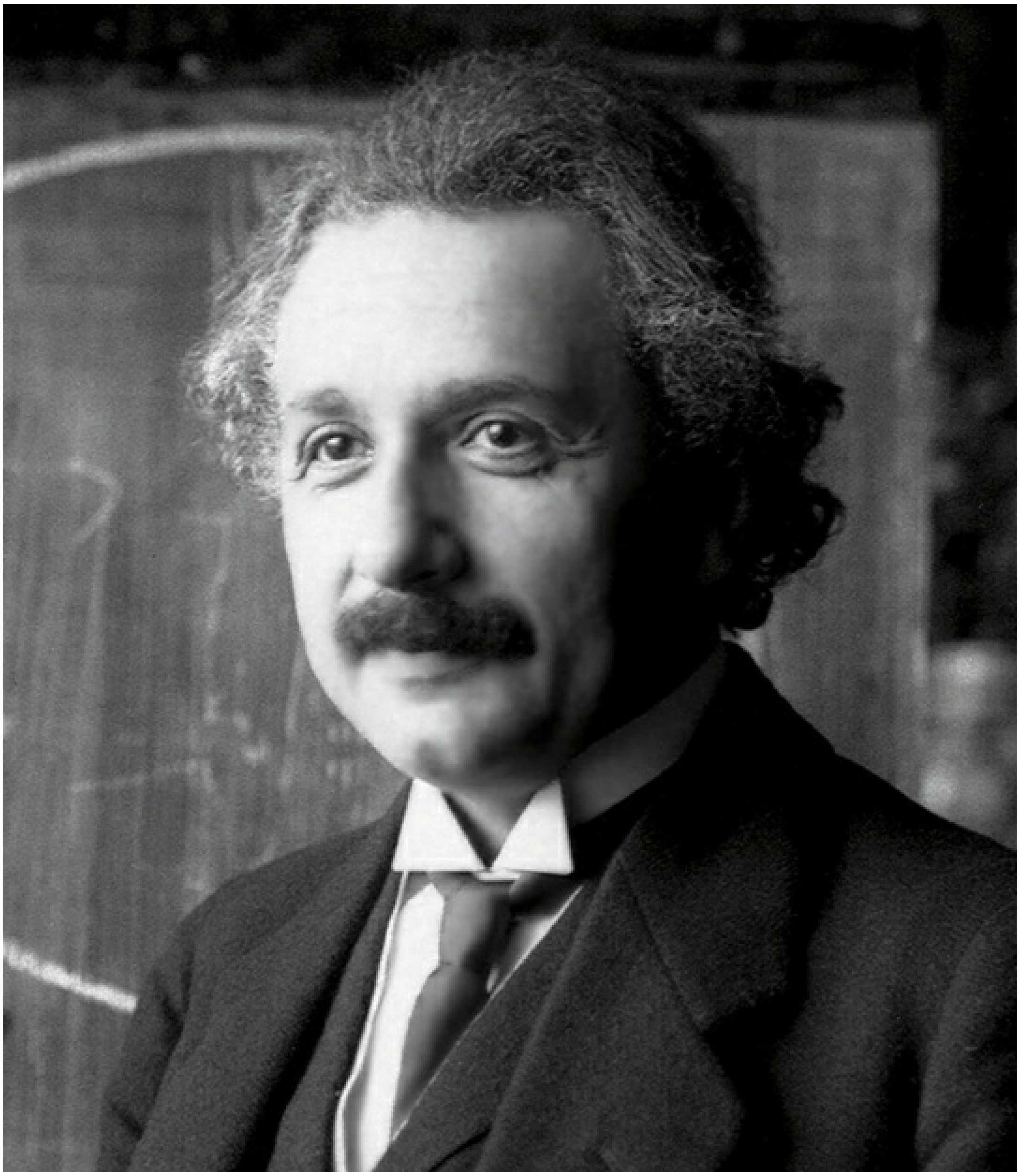
According to many scholars I consulted, there will never be another individual on par with Einstein. Levenson suggested, "It seems unlikely that [science] will produce another Einstein in the sense of a broadly recognized emblem of genius. The sheer complexity of models being explored [today] confines almost all practitioners to *parts* of the problem." Unlike today's scientists, Einstein required little or no collaboration. Einstein's paper on special relativity contained no references to others or to prior work.

Bran Ferren, cochairman and chief creative officer of the Applied Minds technology company, affirms that "the *idea* of Einstein is perhaps more important than Einstein himself." Not only was Einstein the greatest physicist of the modern world, he was an “inspirational role model whose life and work ignited the lives of countless other great thinkers. The total of their contributions to society, and the contributions of the thinkers whom they will in turn inspire, will greatly exceed those of Einstein himself.”

Einstein created an unstoppable “intellectual chain reaction,” an avalanche of pulsing, chattering neurons and memes that will ring for an eternity.

SEE ALSO Newton as Inspiration (1687), $E = mc^2$ (1905), Special Theory of Relativity (1905), Photoelectric Effect (1905), General Theory of Relativity (1915).

Photo of Albert Einstein, while attending a lecture in Vienna in 1921 at the age of 42.



1924

De Broglie Relation • *Clifford A. Pickover*

Louis-Victor-Pierre-Raymond, 7**th duc de Broglie** (1892–1987), **Clinton Joseph Davisson** (1881–1958), **Lester Halbert Germer** (1896–1971)

Numerous studies of the subatomic world have demonstrated that particles like electrons or photons (packets of light) are not like objects with which we interact in our everyday lives. These entities appear to possess characteristics of both waves and particles, depending on the experiment or phenomena being observed. Welcome to the strange realm of quantum mechanics.

In 1924, French physicist Louis-Victor de Broglie suggested that particles of matter could also be considered as waves and would possess properties commonly associated with waves, including a wavelength (the distance between successive crests of wave). In fact, all bodies have a wavelength. In 1927, American physicists Clinton Davisson and Lester Germer demonstrated the wave nature of electrons by showing that they could be made to diffract and interfere as if they were light.

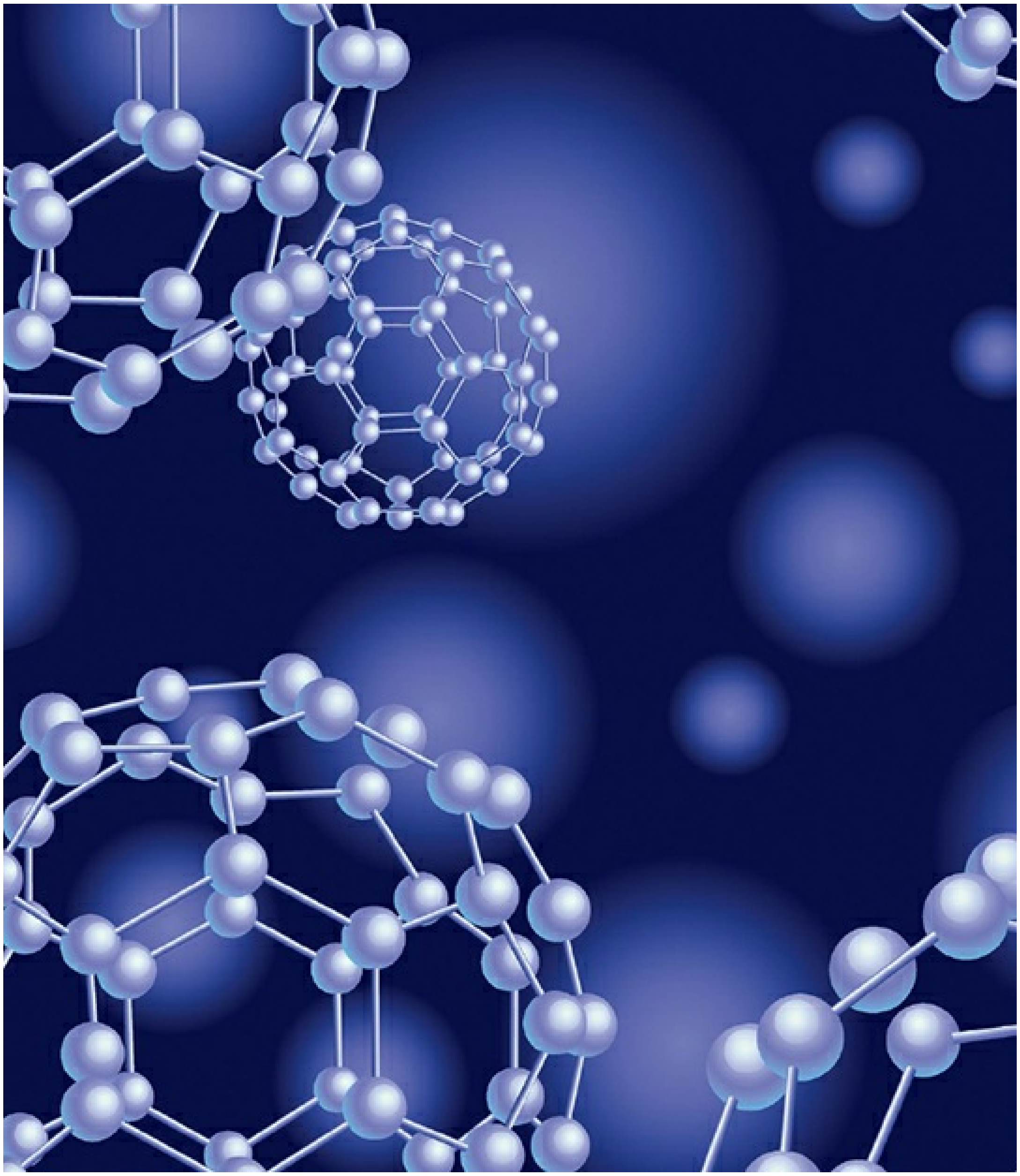
De Broglie's famous relationship showed that the wavelength of a matter wave is inversely proportional to the particle's *momentum* (generally speaking, mass times velocity), and, in particular, $\lambda = h/p$. Here, λ is the wavelength, p is the momentum, and h is Planck's constant. According to author Joanne Baker, using this equation, it is possible to show that "Bigger objects, like ball bearings and badgers, have minuscule wavelengths, too small to see, so we cannot spot them behaving like waves. A tennis ball flying across a court has a wavelength of 10^{-34} meters, much smaller than a proton's width (10^{-15} m)." The wavelength of an ant is larger than for a human.

Since the original Davisson-Germer experiment for electrons, the de Broglie hypothesis has been confirmed for other particles like neutrons and protons and, in 1999, even for entire molecules such a buckyballs, soccer-ball-shaped molecules made of carbon atoms.

De Broglie had advanced his idea in his PhD thesis, but the idea was so radical that his thesis examiners were, at first, not sure if they should approve the thesis. He later won the Nobel Prize for this work.

SEE ALSO Wave Nature of Light (1801), Electron (1897), Schrödinger's Wave Equation (1926).

In 1999, University of Vienna researchers demonstrated the wavelike behavior of buckminsterfullerene molecules formed of 60 carbon atoms (shown here). A beam of molecules (with velocities of around 200 m/sec, or 656 ft/sec) were sent through a grating, yielding an interference pattern characteristic of waves.



1925

Pauli Exclusion Principle • *Clifford A. Pickover*

Wolfgang Ernst Pauli (1900–1958)

Imagine people who are beginning to fill the seats in a baseball stadium, starting at the rows nearest the playing field. This is a metaphor for electrons filling the orbitals of an atom—and in both baseball and atomic physics, there are rules that govern how many entities such as electrons or people can fill the allotted areas. After all, it would be quite uncomfortable if multiple people attempted to squeeze into a small seat.

Pauli's Exclusion Principle (PEP) explains why matter is rigid and why two objects cannot occupy the same space. It's why we don't fall through the floor and why neutron stars resist collapsing under their own incredible mass.

More specifically, PEP states that no pair of identical fermions (such as electrons, protons, or neutrons) can simultaneously occupy the same quantum state, which includes the spin of a fermion. For example, electrons occupying the same atomic orbital must have opposite spins. Once an orbital is occupied by a pair of electrons of opposite spin, no more electrons may enter the orbital until one leaves the orbital.

PEP is well-tested, and one of the most important principles in physics. According to author Michela Massimi, "From spectroscopy to atomic physics, from quantum field theory to high-energy physics, there is hardly another scientific principle that has more far-reaching implications than Pauli's exclusion principle." As a result of PEP, one can determine or understand electronic configurations underlying the classification of chemical elements in the Periodic Table as well as atomic spectra. Science-journalist

Andrew Watson writes, “Pauli introduced this principle early in 1925, before the advent of modern quantum theory or the introduction of the idea of electron spin. His motivation was simple: there had to be something to prevent all the electrons in an atom collapsing down to a single lowest state. . . . So, Pauli’s exclusion principle keeps electrons—and other fermions—from invading each other’s space.”

SEE ALSO Coulomb’s Law of Electrostatics (1785), Electron (1897), Bohr Atom (1913), Neutron Star (1933).

Artwork titled “Pauli’s Exclusion Principle, or Why Dogs Don’t Suddenly Fall Through Solids.” PEP helps explain why matter is rigid, why we do not fall through solid floors, and why neutron stars resist collapsing under their humongous masses.

1926

Schrödinger's Wave Equation • *Clifford A. Pickover*

Erwin Rudolf Josef Alexander Schrödinger (1887–1961)

"Schrödinger's Wave Equation enabled scientists to make detailed predictions about how matter behaves, while being able to visualize the atomic systems under study," writes physicist Arthur I. Miller. Schrödinger apparently developed his formulation while vacationing at a Swiss ski resort with his mistress who seemed to catalyze his intellectual and "erotic outburst," as he called it. The Schrödinger Wave Equation describes ultimate reality in terms of wave functions and probabilities. Given the equation, we can calculate the wave function of a particle:

$$i\hbar \frac{\partial}{\partial t}\psi(\mathrm{r},t) = -\frac{\hbar^2}{2m}\nabla^2\psi(\mathrm{r},t) + V(\mathrm{r})\psi(\mathrm{r},t)$$

Here, we need not worry about the details of this formula, except perhaps to note that $\psi(\mathrm{r}, t)$ is the wave function, which is the probability amplitude for a particle to have a given position r at any given time t. ∇^2 is used to describe how $\psi(\mathrm{r}, t)$ changes in space. $V(\mathrm{r})$ is the potential energy of the particle at each position r. Just as an ordinary wave equation describes the progression of a ripple across a pond, Schrödinger's Wave Equation describes how a probability wave associated with a particle (e.g. an electron) moves through space. The peak of the wave corresponds to where the particle is most likely to be. The equation was also useful in understanding energy levels of electrons in atoms and became one of the foundations of quantum mechanics, the physics of the atomic world. Although it may seem odd to describe a particle as a wave, in the quantum realm such strange dualities are necessary. For example, light can act as either a wave or a particle (a photon), and particles such as electrons and protons can act as waves. As another analogy, think of electrons in an atom as waves on a drumhead, with the vibration modes of the wave equation associated with different energy levels of atoms.

Note that the *matrix mechanics* developed by Werner Heisenberg, Max Born, and Pascual Jordan in 1925 interpreted certain properties of particles in terms of matrices. This formulation is equivalent to the Schrödinger wave formulation.

SEE ALSO Wave Nature of Light (1801), Electron (1897), De Broglie Relation (1924), Heisenberg Uncertainty Principle (1927), Dirac Equation (1928), Schrödinger's Cat (1935).

Erwin Schrödinger on a 1000 Austrian schilling banknote (1983).


TAUSEND
SCHILLING
OESTERREICHISCHE
NATIONALBANK
PRÄSIDENT
GENERALRAT
GENERALDIREKTOR
1000
ERWIN SCHRÖDINGER
1000
G992654H
G992654H
UNIVERSITÄT WIEN
TAUSEND SCHILLING
1000

1927

Complementarity Principle • *Clifford A. Pickover*

Niels Henrik David Bohr (1885–1962)

Danish physicist Niels Bohr developed a concept that he referred to as *complementarity* in the late 1920s, while trying to make sense of the mysteries of quantum mechanics, which suggested, for example, that light sometimes behaved like a wave and at other times like a particle. For Bohr, writes author Louisa Gilder, “complementarity was an almost religious belief that the paradox of the quantum world must be accepted as fundamental, not to be ‘solved’ or trivialized by attempts to find out ‘what’s really going on down there.’ Bohr used the word in an unusual way: ‘the complementarity’ of waves and particles, for example (or of position and momentum), meant that when one existed fully, its complement did not exist at all.” Bohr himself in a 1927 lecture in Como, Italy, said that waves and particles are “abstractions, their properties being definable and observable only through their interactions with other systems.”

Sometimes, the physics and philosophy of complementarity seemed to overlap with theories in art. According to science-writer K. C. Kole, Bohr “was known for his fascination with cubism—especially ‘that an object could be several things, could change, could be seen as a face, a limb, a fruit bowl,’ as a friend of his later explained. Bohr went on to develop his philosophy of complementarity, which showed how an electron could change, could be seen as a wave [or] a particle. Like cubism, complementarity allowed contradictory views to coexist in the same natural frame.”

Bohr thought that it was inappropriate to view the subatomic world from our everyday perspective. “In our description of nature,” Bohr wrote, “the purpose is not to disclose the real essence of phenomena but only to track down, as far as it is possible, relations between the manifold aspects of experience.”

In 1963, physicist John Wheeler expressed the importance of this principle: “Bohr’s principle of complementarity is the most revolutionary scientific concept of this century and the heart of his fifty-year search for the full significance of the quantum idea.”

SEE ALSO Wave Nature of Light (1801), Heisenberg Uncertainty Principle (1927), Schrödinger’s Cat (1935), EPR Paradox (1935), Parallel Universes (1956).

The physics and philosophy of complementarity often seemed to overlap with theories in art. Bohr was fascinated with Cubism, which sometimes allowed “contradictory” views to coexist, as in this artwork by Czech painter Eugene Ivanov.

1927

Food Webs • *Michael C. Gerald with Gloria E. Gerald*

Al-Jahiz (781–868/869), **Charles Elton** (1900–1991), **Raymond Lindeman** (1915–1942)

The concept of a food chain originated with Al-Jahiz, a ninth-century Arabic author of some two hundred books on a wide range of subjects including grammar, poetry, and zoology. In his zoology work, he discussed a struggle for existence among animals who hunt to obtain food and who are, in turn, hunted. Charles Elton, an Oxford faculty member, was among the most important animal ecologists of the twentieth century. In his classic 1927 text *Animal Ecology*, Elton laid out the basic principles of modern ecology, including, rather explicitly, food chains and food webs, which are now central themes in ecology.

At its simplest level, a food cycle follows a linear relationship from the base of the food chain—a species that eats no other (typically, a plant)—to the final predator or ultimate consumer, which is typically three to six feeding levels in length. Elton recognized that this simple food chain depiction was a gross oversimplification of "who eats whom." The food chain failed to account for real ecosystems, in which there are multiple predators and multiple preys, and the reality that a given animal might consume other animals if the preferred prey was not available. Moreover, some carnivores also eat plant material and are omnivores; conversely, herbivores occasionally eat meat. The food web, a concept now preferred to food chain, represents these highly complex interrelationships.

In 1942, Raymond Lindeman postulated that the number of levels in a food chain is limited by *trophic dynamics*, or the effective transfer of energy from one part of the ecosystem to another. After food is consumed, energy is stored in the body of the consumer, and it travels in only one direction. Much of that energy is lost as heat (when the food is being utilized for basic needs), and the remainder eliminated as waste material. In general, only about 10 percent of the energy consumed is available at the next higher trophic (feeding) level. Thus, with each successive level up the chain, less energy is transmitted and, therefore, food chains rarely exceed four to five feeding levels.

SEE ALSO Agriculture (c. 10,000 BCE) Ecological Interactions (1859), Insect Dance Language (1927).

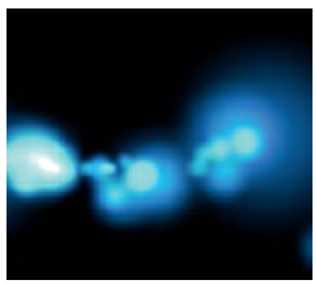
The food web is exemplified at Katmai National Park, Alaska, where this grizzly bear is a jawful away from eating a fish, which fed on a smaller fish or microscopic plants or animals floating in the water.

1927

Heisenberg Uncertainty Principle •

Clifford A. Pickover

Werner Heisenberg (1901–1976)



“Uncertainty is the only certainty there is,” wrote mathematician John Allen Paulos, “and knowing how to live with insecurity is the only security.” The Heisenberg Uncertainty Principle states that the position and the velocity of a particle cannot both be known with high precision, at the same time. Specifically, the more precise the measurement of position, the more imprecise the measurement of momentum, and vice versa. The uncertainty principle becomes significant at the small size scales of atoms and subatomic particles.

Until this law was discovered, most scientists believed that the precision of any measurement was limited only by the accuracy of the instruments being used. German physicist Werner Heisenberg hypothetically suggested that even if we could construct an infinitely precise measuring instrument, we still could not accurately determine both the position and momentum (mass × velocity) of a particle. The principle is not concerned with the degree to which the measurement of the position of a particle may *disturb* the momentum of a particle. We could measure a particle’s position to a high precision, but as a consequence, we could know little about the momentum.

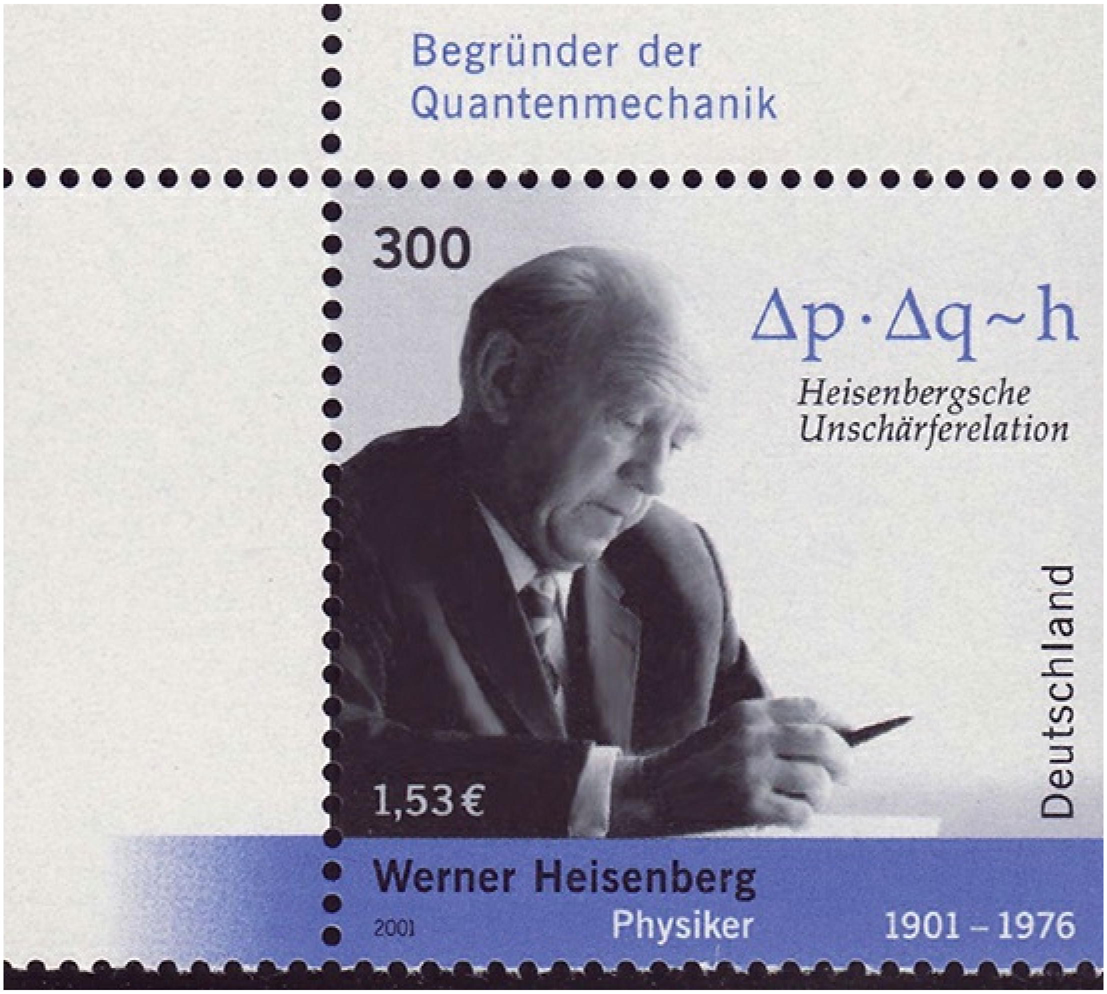
For those scientists who accept the Copenhagen interpretation of quantum mechanics, the Heisenberg Uncertainty Principle means that the physical Universe literally does not exist in a deterministic form but is rather a collection of probabilities. Similarly, the path of an elementary particle such as a photon cannot be predicted, even in theory, by an infinitely precise measurement.

In 1935, Heisenberg was a logical choice to replace his former mentor Arnold Sommerfeld at the University of Munich. Alas, the Nazis required that "German physics" must replace "Jewish physics," which included quantum theory and relativity. As a result, Heisenberg's appointment to Munich was blocked even though he was not Jewish.

During World War II, Heisenberg led the unsuccessful German nuclear weapons program. Today, historians of science still debate as to whether the program failed because of lack of resources, lack of the right scientists on his team, Heisenberg's lack of a desire to give such a powerful weapon to the Nazis, or other factors.

SEE ALSO Bohr Atom (1913), Schrödinger's Wave Equation (1926), Complementarity Principle (1927).

LEFT: *According to Heisenberg's Uncertainty Principle, particles likely exist only as a collection of probabilities, and their paths cannot be predicted even by an infinitely precise measurement.* RIGHT: *German postage stamp, 2001, featuring Werner Heisenberg.*


Begründer der
Quantenmechanik
300
Δp·Δq~h
Heisenbergsche
Unschärferelation
Deutschland
1,53 €
Werner Heisenberg
2001
Physiker
1901 – 1976

1927

Insect Dance Language • *Michael C. Gerald with Gloria E. Gerald*

Karl von Frisch (1886–1982)

Animals communicate with one another when seeking to locate food, mate, or signal an alarm in the presence of threats in their environment. A variety of animals use pheromones to facilitate various phases of their mating behavior. Not all communication occurs between members of the same animal species, such as the facial expression and body language of our pets. The odor from a skunk's spray is a highly effective defensive weapon used to ward off bears and other potential predators, and it is sufficiently pungent that it can be detected by human noses at downwind distances of one mile (1.6 kilometers).

Animal communication is not limited to vertebrates, with some of the most interesting examples occurring in insects. Pioneering studies on insect communications were conducted in the 1920s by the Nobel laureate Karl von Frisch, an Austrian ethnologist at the University of Munich. He observed that a distinctive "dance language" is used by European honeybee (*Apis mellifera*) foragers to inform other bees in the hive about the direction and distance of food. A "round dance," in which the forager executes tight circles, is performed when food is close to the hive—less than 160–320 feet (50–100 meters)—whereas a "waggle dance," resembling a figure-eight movement, signifies food at a distant location.

European honeybees also use a complex chain of communication modes that involve all five senses in a fascinating courtship ritual, with each signaling and triggering a subsequent behavior by the partner: The male visually identifies the female and turns toward her. The female releases a chemical that is detected by the male's olfactory system. He approaches the female and taps her with his limb that, in the process, picks up the chemical. In response, the male extends and vibrates his wings producing a "courtship song," a form of auditory communication. Only after this entire sequence is successively and successfully completed will the female allow the male to perform copulation.

SEE ALSO Ecological Interactions (1859), Neuron Doctrine (1891), Food Webs (1927).

Dance language among certain insects—in particular, honeybees—is well developed and has been extensively studied. Here, the Apis cerana japonica honeybees surround their nest in Japan.

1928

Dirac Equation • *Clifford A. Pickover*

Paul Adrien Maurice Dirac (1902–1984)

As discussed in the entry on antimatter, the equations of physics can sometimes give birth to ideas or consequences that the discoverer of the equation did not expect. The power of these kinds of equations can seem magical, according to physicist Frank Wilczek in his essay on the Dirac Equation. In 1927, Paul Dirac attempted to find a version of Schrödinger's Wave Equation that would be consistent with the principles of special relativity. One way that the Dirac Equation can be written is

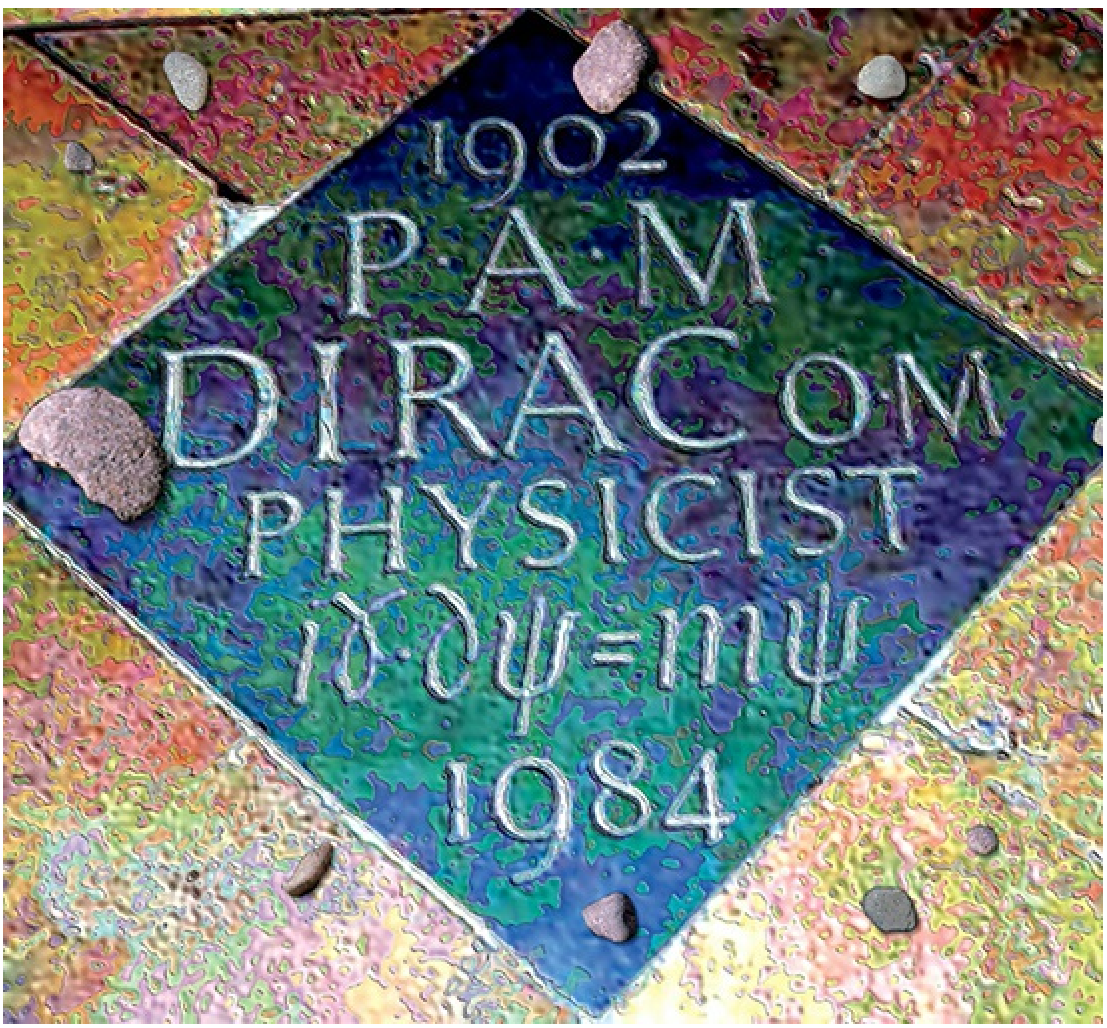
$$\left(\alpha_0 mc^2 + \sum_{j=1}^{3} \alpha_j p_j c\right)\Psi(\mathrm{x},t) = i\hbar\,\frac{\partial \Psi}{\partial t}(\mathrm{x},t)$$

Published in 1928, the equation describes electrons and other elementary particles in a way that is consistent with both quantum mechanics and the Special Theory of Relativity. The equation predicts the existence of antiparticles and in some sense "foretold" their experimental discovery. This feature made the discovery of the positron, the antiparticle of the electron, a fine example of the usefulness of mathematics in modern theoretical physics. In this equation, m is the rest mass of the electron, $\hbar$ is the reduced Planck's constant (1.054×10^{-34} J·s), c is the speed of light, p is the momentum operator, x and t are the space and time coordinates, and $\Psi(\mathrm{x},t)$ is a wave function. α is a linear operator that acts on the wave function.

Physicist Freeman Dyson has lauded this formula that represents a significant stage in humanity's grasp of reality. He writes, "Sometimes the understanding of a whole field of science is suddenly advanced by the discovery of a single basic equation. Thus it happened that the Schrödinger equation in 1926 and the Dirac equation in 1927 brought a miraculous order into the previously mysterious processes of atomic physics. Bewildering complexities of chemistry and physics were reduced to two lines of algebraic symbols."

SEE ALSO Electron (1897), Special Theory of Relativity (1905), Schrödinger's Wave Equation (1926), Antimatter (1932).

The Dirac equation is the only equation to appear in Westminster Abbey, London, where it is engraved on Dirac's commemorative plaque. Shown here is an artist's representation of the Westminster plaque, which depicts a simplified version of the formula.



1928

Penicillin • *Clifford A. Pickover*

John Tyndall (1820–1893), **Alexander Fleming** (1881–1955), **Howard Walter Florey** (1898–1968), **Ernst Boris Chain** (1906–1979), **Norman George Heatley** (1911–2004)

Reflecting on his discovery later in life, Scottish biologist Alexander Fleming recalled, “When I woke up just after dawn on September 28, 1928, I certainly didn’t plan to revolutionize all medicine by discovering the world’s first antibiotic, or bacteria killer. But I suppose that was exactly what I did.”

When Fleming returned from a vacation, he noticed that mold had developed on his contaminated culture plate of the bacterium *Staphylococcus*. He also noticed that the bacterial growth was inhibited near the mold, so he concluded that the mold was releasing a substance that repressed bacterial growth. He soon grew a pure mold culture in broth, determined the mold to be of the *Penicillium* genus, and referred to the antibiotic substance in the broth as penicillin. Interestingly, many ancient societies had noticed that mold could serve as a remedy, and Irish physicist John Tyndall even demonstrated the antibacterial action of the *Penicillium* fungus in 1875. However, Fleming was probably the first to suggest that this mold secreted an antibacterial substance and then isolate it. Later studies showed that penicillin works by weakening the cell walls of bacteria.

In 1941, Australian pharmacologist Howard Florey, German biochemist Ernst Chain, and English biochemist Norman Heatley, while working together in England, were finally able to turn penicillin into a usable drug, showing that it cured infections in mice and people. The U.S. and British governments were determined to produce as much penicillin as possible to help their soldiers during World War II, and a moldy cantaloupe in Peoria, Illinois, produced more than two million doses before 1944. Penicillin was soon used to defeat major bacterial diseases, such as blood poisoning, pneumonia, diphtheria, scarlet fever, gonorrhea, and syphilis. Unfortunately, antibiotic-resistant bacterial strains have evolved, necessitating the quest for additional antibiotics.

Molds are not the only producers of natural antibiotics. For example, the bacterium *Streptomyces* was the source of streptomycin and the tetracyclines. Penicillin and these later-discovered antibiotics triggered a revolution in the battle against disease.

SEE ALSO Germ Theory of Disease (1862), Antiseptics (1865), Chlorination of Water (1910).

Close-up image of the Penicillium fungus, which produces penicillin.

1929

Hubble’s Law of Cosmic Expansion •

Clifford A. Pickover

Edwin Powell Hubble (1889–1953)

“Arguably the most important cosmological discovery ever made,” writes cosmologist John P. Huchra, “is that our Universe is expanding. It stands, along with the Copernican Principle—that there is no preferred place in the Universe, and Olbers’ Paradox—that the sky is dark at night, as one of the cornerstones of modern cosmology. It forced cosmologists to [consider] dynamic models of the Universe, and also implies the existence of a timescale or age for the Universe. It was made possible . . . primarily by Edwin Hubble’s estimates of distances to nearby galaxies.”

In 1929, American astronomer Edwin Hubble discovered that the greater the distance a galaxy is from an observer on the Earth, the faster it recedes. The distances between galaxies, or galactic clusters, are continuously increasing and, therefore, the Universe is expanding.

For many galaxies, the velocity (e.g. the movement of a galaxy away from an observer on the Earth) can be estimated from the red shift of a galaxy, which is an observed increase in the wavelength of electromagnetic radiation received by a detector on the Earth compared to that emitted by the source. Such red shifts occur because galaxies are moving away from our own galaxy at high speeds due to the expansion of space itself. The change in the wavelength of light that results from the relative motion of the light source and the receiver is an example of the Doppler Effect. Other methods also exist for determining the velocity for faraway galaxies. (Objects that are dominated by local gravitational interactions, like stars within a single galaxy, do not exhibit this apparent movement away from one another.)

Although an observer on the Earth finds that all distant galactic clusters are flying away from the Earth, our location in space is not special. An observer in another galaxy would also see the galactic clusters flying away from the observer's position because all of space is expanding. This is one of the main lines of evidence for the Big Bang from which the early Universe evolved and the subsequent expansion of space.

SEE ALSO Cosmic Microwave Background (1965), Cosmic Inflation (1980), Dark Energy (1998).

For millennia, humans have looked to the skies and wondered about their place in the cosmos. Pictured here are Polish astronomer Johannes Hevelius and his wife Elisabeth making observations (1673). Elisabeth is considered to be among the first female astronomers.

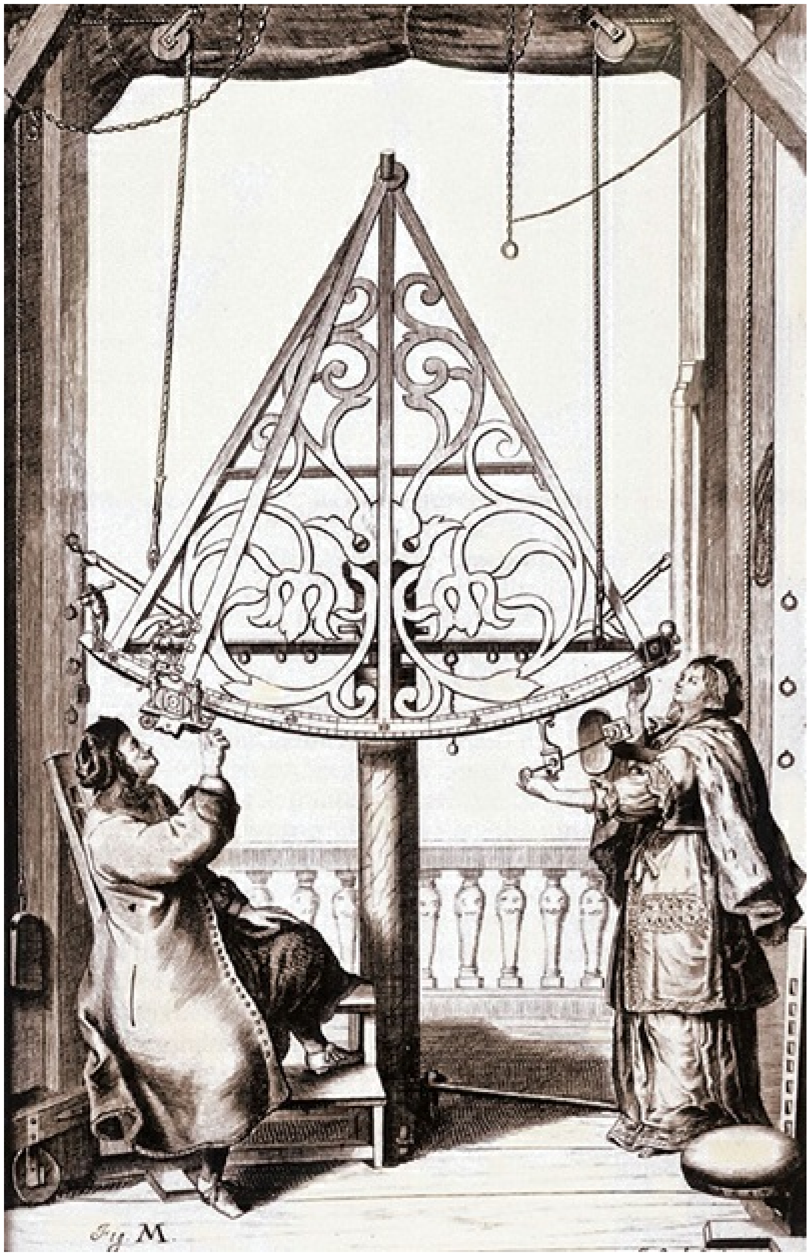


Fig. M.

1931

Gödel’s Theorem • *Clifford A. Pickover*

Kurt Gödel (1906–1978)

Austrian mathematician Kurt Gödel was an eminent mathematician and among the most brilliant logicians of the twentieth century. The implications of his incompleteness theorem are vast, applying not only to mathematics but also touching on areas such as computer science, economics, and physics. When Gödel was at Princeton University, one of his closest friends was Albert Einstein.

Gödel’s theorem, published in 1931, had quite a sobering effect upon logicians and philosophers because it implies that within any rigidly logical mathematical system, propositions or questions exist that cannot be proved or disproved on the basis of axioms within that system, and therefore it is possible for basic axioms of arithmetic to give rise to contradictions. This makes mathematics essentially “incomplete.” The repercussions of this fact continue to be felt and debated. Moreover, Gödel’s theorem put an end to centuries of attempting to establish axioms that would provide a rigorous basis for all of mathematics.

Author Hao Wang writes on this very subject in his book *Reflections on Kurt Gödel*: “The impact of Gödel’s scientific ideas and philosophical speculations has been increasing, and the value of their potential implications may continue to increase. It may take *hundreds of years* for the appearance of more definite confirmations or refutations of some of his larger conjectures.” Douglas Hofstadter notes that a second theorem of Gödel’s also suggests the inherent limitation of mathematical systems and “implies that the only versions of formal number theory which assert their own consistency are inconsistent.”

In 1970, Gödel's mathematical proof of the existence of God began to circulate among his colleagues. The proof was less than a page long and caused quite a stir. Toward the end of his life, Gödel was paranoid and felt that people were trying to poison him. He stopped eating and died in 1978. During his life, he had also suffered from nervous breakdowns and hypochondria.

SEE ALSO Aristotle's *Organon* (c. 350 BCE), Euclid's *Elements* (c. 300 BCE), Cantor's Transfinite Numbers (1874).

Albert Einstein and Kurt Gödel. Photo by Oskar Morgenstern, Institute of Advanced Study Archives, Princeton, 1950s.

1932

Antimatter • *Clifford A. Pickover*

Paul Dirac (1902–1984), **Carl David Anderson** (1905–1991)

“Fictional spaceships are often powered by ‘antimatter drives’,” writes author Joanne Baker, “yet antimatter itself is real and has even been made artificially on the Earth. A ‘mirror image’ form of matter . . ., antimatter cannot coexist with matter for long—both annihilate in a flash of energy if they come into contact. The very existence of antimatter points at deep symmetries in particle physics.”

The British physicist Paul Dirac once remarked that the abstract mathematics we study now gives us a glimpse of physics in the future. In fact, his equations from 1928 that dealt with electron motion predicted the existence of antimatter, which was subsequently discovered. According to the formulas, an electron must have an antiparticle with the same mass but a positive electrical charge. In 1932, U.S. physicist Carl Anderson observed this new particle experimentally and named it the *positron*. In 1955, the antiproton was produced at the Berkeley Bevatron (a particle accelerator). In 1995, physicists created the first anti-hydrogen atom at the CERN research facility in Europe. CERN (*Organisation Européenne pour la Recherche Nucléaire*), or the European Organization for Nuclear Research, is the largest particle physics laboratory in the world.

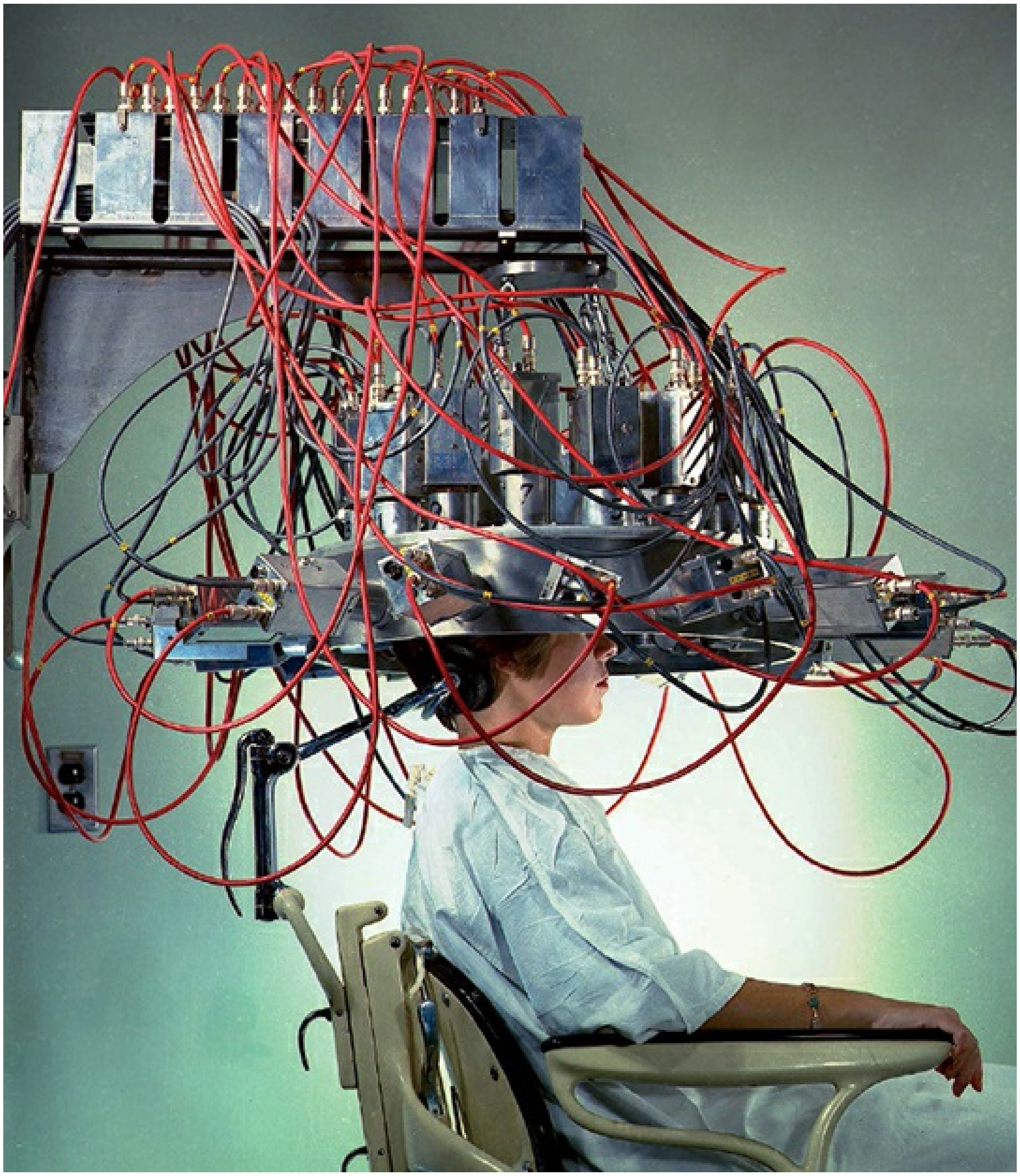
Antimatter-matter reactions have practical applications today in the form of positron emission tomography (PET). This medical imaging technique involves the detection of gamma rays (high-energy radiation) emitted by a positron-emitting tracer radionuclide, an atom with an unstable nucleus.

Modern physicists continue to offer hypotheses to explain why the observable universe appears to be nearly entirely composed of matter and not antimatter. Could regions of the universe exist in which antimatter predominates?

Upon casual inspection, antimatter would be almost indistinguishable from ordinary matter. Physicist Michio Kaku writes, “You can form antiatoms out of antielectrons and antiprotons. Even antipeople and antiplanets are theoretically possible. [However], antimatter will annihilate into a burst of energy upon contact with ordinary matter. Anyone holding a piece of antimatter in their hands would immediately explode with the force of thousands of hydrogen bombs.”

SEE ALSO Electron (1897), Dirac Equation (1928), Little Boy Atomic Bomb (1945).

In the 1960s, researchers at Brookhaven National Laboratory used detectors, such as this, for studying small brain tumors that absorbed injected radioactive material. Breakthroughs led to more practical devices for imaging areas of the brain, such as today’s PET machines.



1932

Neutron • *Clifford A. Pickover*

Sir James Chadwick (1891–1974), **Irène Joliot-Curie** (1897–1956), **Jean Frédéric Joliot-Curie** (1900–1958)

"James Chadwick's road to the discovery of the neutron was long and tortuous," writes chemist William H. Cropper. "Because they carried no electrical charge, neutrons did not leave observable trails of ions as they passed through matter, and left no tracks in Wilson's cloud chamber; to the experimenter, they were invisible." Physicist Mark Oliphant writes, "The neutron was discovered as a result of a persistent search by Chadwick, and not by accident as were radioactivity and X-rays. Chadwick felt intuitively that it must exist and never gave up the chase."

The neutron is a subatomic particle that is part of every atomic nucleus except for ordinary hydrogen. It has no net electric charge and a mass slightly greater than that of a proton. Like the proton, it is composed of three quarks. When the neutron is inside the nucleus, the neutron is stable; however, free neutrons undergo beta decay, a type of radioactive decay, and have a mean lifetime of approximately 15 minutes. Free neutrons are produced during nuclear fission and fusion reactions.

In 1931, Irène Joliot-Curie (daughter of Marie Curie, the first person honored with two Nobel Prizes) and her husband Frédéric Joliot described a mysterious radiation produced by bombarding beryllium atoms with alpha particles (helium nuclei), and this radiation caused protons to be knocked loose from hydrogen-containing paraffin. In 1932, James Chadwick conducted additional experiments and suggested that this new kind of radiation was composed of uncharged particles of approximately the mass of the proton, namely, *neutrons*. Because the free neutrons are uncharged, they are not hindered by electrical fields and penetrate deeply into matter.

Later, researchers discovered that various elements, when bombarded by neutrons, undergo fission—a nuclear reaction that occurs when the nucleus of a heavy element splits into two nearly equal smaller pieces. In 1942, researchers in the U.S. showed that these free neutrons produced during fission can create a chain reaction and enormous amounts of energy, and could be used to create an atomic bomb—and nuclear power plants.

SEE ALSO Radioactivity (1896), Atomic Nucleus (1911), Neutron Star (1933), Energy from the Nucleus (1942), Standard Model (1961), Quark (1964).

The Brookhaven Graphite Research Reactor—the first peacetime reactor to be constructed in the United States following World War II. One purpose of the reactor was to produce neutrons via uranium fission for scientific experimentation.

1933

Dark Matter • *Clifford A. Pickover*

Fritz Zwicky (1898–1974), **Vera Cooper Rubin** (1928–2016)

Astronomer Ken Freeman and science-educator Geoff McNamara write, “Although science teachers often tell their students that the periodic table of the elements shows what the Universe is made of, this is not true. We now know that most of the Universe—about 96% of it—is made of dark material [dark matter and dark energy] that defies brief description. . . .” Whatever the composition of dark matter is, it does not emit or reflect sufficient light or other forms of electromagnetic radiation to be observed directly. Scientists infer its existence from its gravitational effects on visible matter such as the rotational speeds of galaxies.

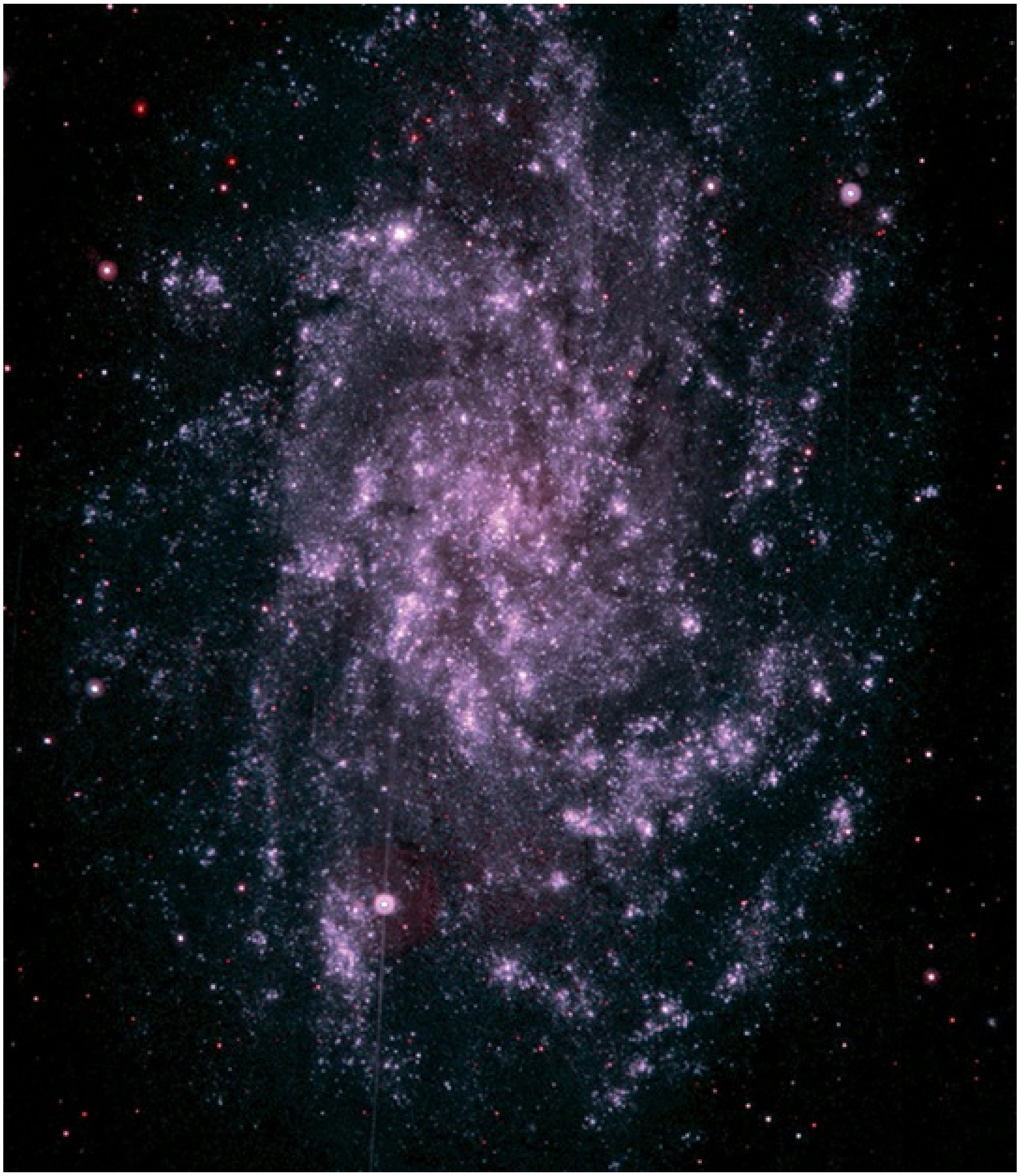
Most of the dark matter probably does not consist of the standard elementary particles—such as protons, neutrons, electrons and known neutrinos—but rather hypothetical constituents with exotic-sounding names such as sterile neutrinos, axions, and WIMPs (Weakly Interacting Massive Particles, including neutralinos), which do not interact with electromagnetism and thus cannot be easily detected. The hypothetical neutralinos are similar to neutrinos, but heavier and slower. Theorists also consider the wild possibility that dark matter includes gravitons, hypothetical particles that transmit gravity, leaking into our universe from neighboring universes. If our universe is on a membrane “floating” within a higher dimensional space, dark matter may be explained by ordinary stars and galaxies on nearby membrane sheets.

In 1933, the astronomer Fritz Zwicky provided evidence for the existence of dark matter through his studies of the motions of the edges of galaxies, which suggested a significant amount of galactic mass was undetectable. In the late 1960s, astronomer Vera Rubin showed that most stars in spiral galaxies orbit at approximately the same speed, which implied the existence of dark matter beyond the locations of stars in the galaxies. In 2005, astronomers from Cardiff University believed they had discovered a galaxy in the Virgo Cluster made almost entirely of dark matter.

Freeman and McNamara write, “Dark matter provides a further reminder that we humans are not essential to the Universe. . . . We are not even made of the same stuff as most of the universe. . . . Our Universe is made of darkness.”

SEE ALSO Newton’s Laws of Motion and Gravitation (1687), Black Holes (1783), Dark Energy (1998).

One early piece of evidence for the existence of dark matter is the 1959 observation of astronomer Louise Volders who demonstrated that spiral galaxy M33 (pictured here in a NASA Swift Satellite ultraviolet image) does not spin as expected according to standard Newtonian dynamics.



1933

Polyethylene • *Derek B. Lowe*

Reginald Oswald Gibson (1902–1983), **Michael Wilcox Perrin** (1905–1988), **Eric Fawcett** (1927–2000)

The year 1933 marks the first industrial synthesis of polyethylene, but (unfortunately) not the first reliable one. It had originally been prepared in 1898 in an accident during German chemist Hans von Pechmann's work with pure diazomethane. No one was foolhardy enough to work with the explosive and toxic diazomethane on a larger scale, so this remained a chemical footnote until British chemist Reginald Oswald Gibson and British-Canadian physicist Eric Fawcett tried a high-pressure, high-temperature reaction between ethylene gas and benzaldehyde (the same compound that inspired the work of German chemists Friedrich Wöhler and Justus von Liebig on functional groups back in 1832). The white, waxy polymer they produced turned out to be all long chains of CH_2 (methylene) groups from the polymerized ethylene, and, with its resistance to chemicals and solvents and its malleability, it seemed as if it could be a very useful material.

Getting the reaction to work reproducibly, however, was very frustrating until British chemist Michael Wilcox Perrin figured out the right conditions in 1937. Traces of oxygen, as it happened, caused that first reaction's accidental success, and later routes used small amounts of more reliable free radical initiators under milder conditions. Polyethylene became a secret material of World War II when its use as an insulator in electronics (such as radar equipment) was discovered. By the end of the war, it was being made on a large scale, and its many forms (hard blocks, thin sheets, flexible panels) were beginning to be appreciated.

Today polyethylene is the most common plastic polymer in the world. Depending on how it’s made (how long the chains are, whether any branching compounds are added to the mix, and so on), it can take on a huge variety of properties, from flexible (low-density polyethylene, or LDPE) to rigid (high-density polyethylene, or HDPE). Hundreds of millions of tons are made each year, and it’s found in products as varied as squeeze bottles, trash bags, sporting goods, and toys. Research on it is still continuing—all in all, an impressive performance for something whose first preparations were all mistakes.

SEE ALSO Rubber (1839), Plastic (1856), Doped Silicon (1941).

Versatile polyethylene is incorporated into countless products and materials, including puncture-resistant fencing gear.

1933

Neutron Stars • *Clifford A. Pickover*

Fritz Zwicky (1898–1974), **Jocelyn Bell Burnell** (b. 1943), **Wilhelm Heinrich Walter Baade** (1893–1960)

Stars are born when a large amount of hydrogen gas starts to collapse in on itself due to gravitational attraction. As the star coalesces, it heats up, produces light, and helium is formed. Eventually the star runs out of hydrogen fuel, starts to cool, and enters one of several possible “graveyard states” such as a black hole or one of its crushed cousins such as a white dwarf (for relatively small stars) or a neutron star.

More particularly, after a massive star has finished burning its nuclear fuel, the central region collapses due to gravity, and the star undergoes a supernova explosion, blowing off its outer layers. A neutron star, made almost entirely of uncharged subatomic particles called neutrons, may be created by this gravitational collapse. A neutron star is prevented from achieving the complete gravitational collapse of a black hole due to the Pauli Exclusion Principle repulsion between neutrons. A typical neutron star has a mass between about 1.4 and 2 times the mass of our Sun, but with a radius of only around 7.5 miles (12 kilometers). Interestingly, neutron stars are formed of an extraordinary material, known as *neutronium*, which is so dense that a sugar cube could contain the crushed mass of the entire human population.

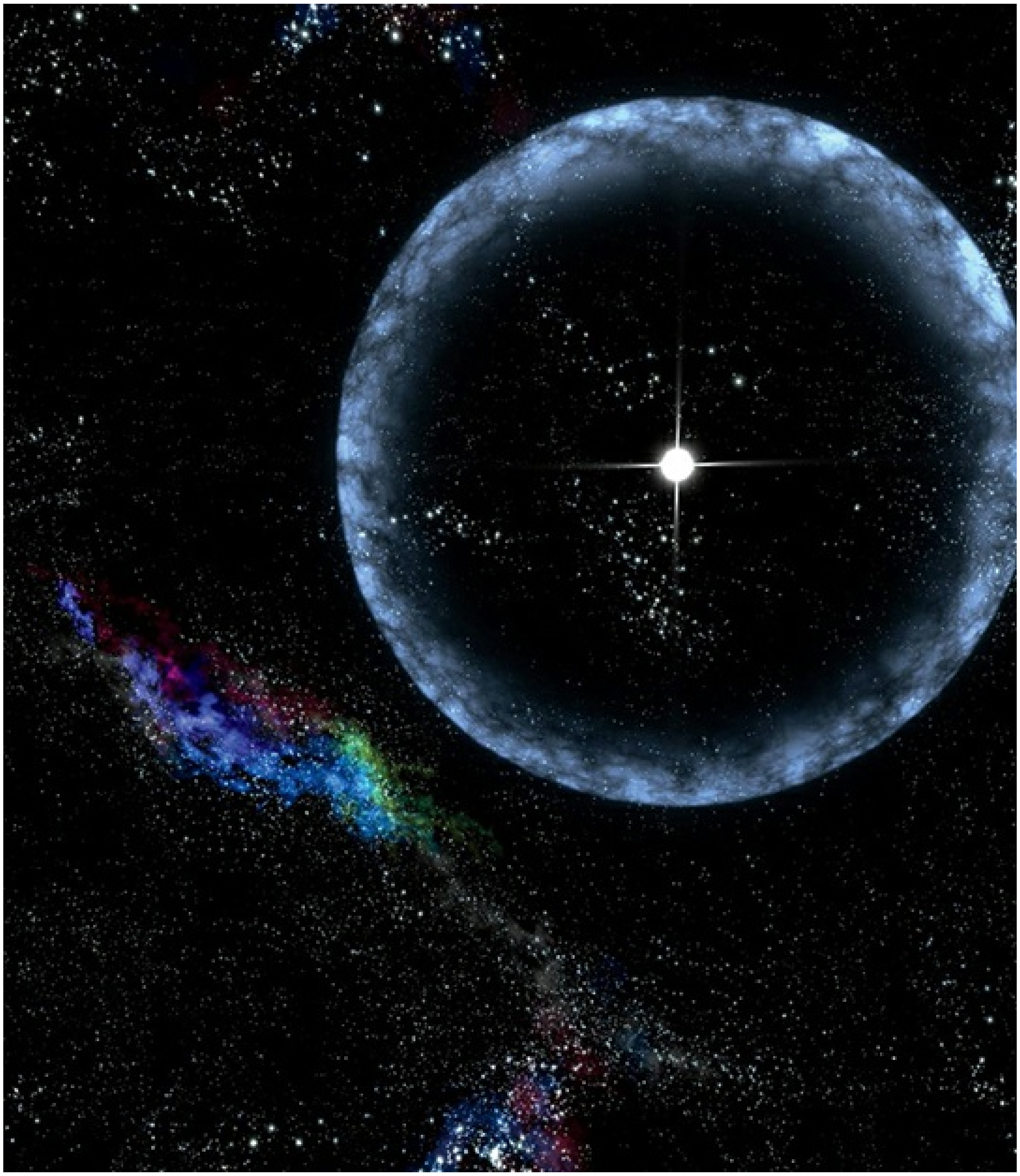
Pulsars are rapidly rotating, highly magnetic neutron stars that send out steady electromagnetic radiation that arrives at the Earth as pulses due to the star’s rotation. The pulses are at intervals ranging from milliseconds to several seconds. The fastest millisecond pulsars spin over 700 times per second! Pulsars were discovered in 1967 by graduate student Jocelyn Bell

Burnell in the form of radio sources that seemed to blink at a constant frequency. In 1933, astrophysicists Fritz Zwicky and Walter Baade proposed the existence of a neutron star, only a year after the discovery of the neutron.

In the novel *Dragon's Egg*, creatures live on a neutron star, where the gravity is so strong that mountain ranges are about a centimeter high.

SEE ALSO Black Holes (1783), Main Sequence (1910), Pauli Exclusion Principle (1925), Neutron (1932).

In 2004, a neutron star underwent a "star quake," causing it to flare brightly, temporarily blinding all X-ray satellites. The blast was created by the star's twisting magnetic fields that can buckle the surface of the neutron star. (Artist's concept from NASA.)



1935

EPR Paradox • *Clifford A. Pickover*

Albert Einstein (1879–1955), **Boris Podolsky** (1896–1966), **Nathan Rosen** (1909–1995), **Alain Aspect** (b. 1947)

Quantum entanglement (QE) refers to an intimate connection between quantum particles, such as between two electrons or two photons. Once the pair of particles is *entangled*, a particular kind of change to one of them is reflected instantly in the other, and it doesn't matter if the pair is separated by inches or by interplanetary distances. This entanglement is so counterintuitive that Albert Einstein referred to it as being "spooky" and thought that it demonstrated a flaw in quantum theory, particularly the Copenhagen interpretation that suggested quantum systems, in a number of contexts, existed in a probabilistic limbo until observed and then reached a definite state.

In 1935, Albert Einstein, Boris Podolsky, and Nathan Rosen published a paper on their famous EPR paradox. Imagine two particles that are emitted by a source so that their spins are in a quantum superposition of opposite states, labeled + and −. Neither particle has a definite spin before measurement. The particles fly apart, one going to Florida and the other to California. According to QE, if scientists in Florida measure the spin and finds a +, the California particle *instantly* assumes the − state, even though the speed of light prohibits faster-than-light (FTL) communication of information. Note, however, that no FTL communication of information has actually occurred. Florida cannot use entanglement to send messages to California because Florida does not manipulate the spin of its particle, which has a 50-50 chance of being in a +

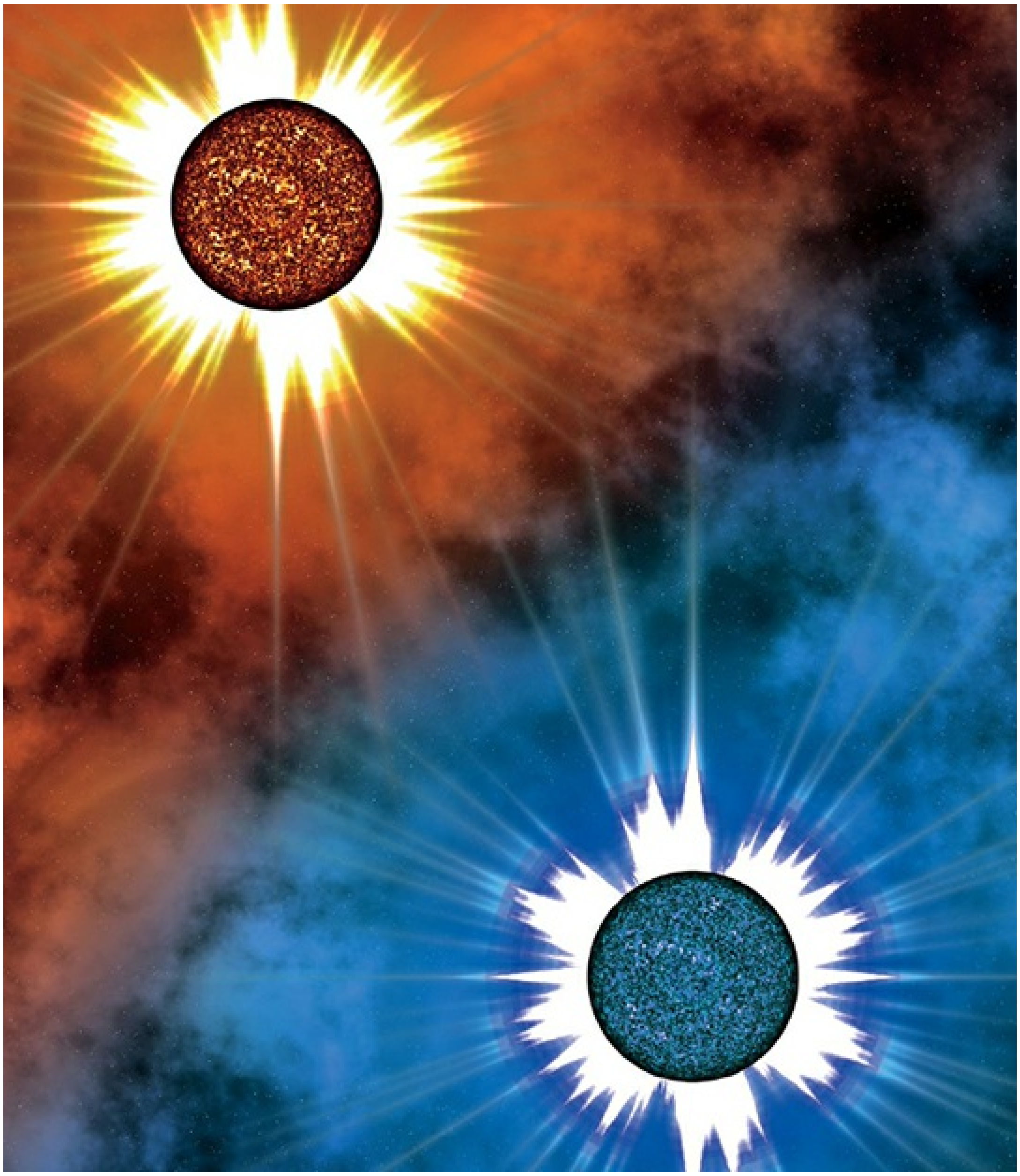
or − state.

In 1982, physicist Alain Aspect performed experiments on oppositely directed photons that were emitted in a single event from the same atom, thus ensuring the photon pairs were correlated. He showed that the instantaneous connection in the EPR paradox actually did take place, even when the particle pair was separated by an arbitrarily large distance.

Today, quantum entanglement is being studied in the field of quantum cryptography to send messages that cannot be spied upon without leaving some kind of trace. Simple Quantum Computers are now being developed that perform calculations in parallel and more quickly than by traditional computers.

SEE ALSO Complementarity Principle (1927), Schrödinger’s Cat (1935), Quantum Computers (1981).

Artist’s rendition of “spooky action at a distance.” Once a pair of particles is entangled, a particular kind of change to one of them is reflected instantly in the other, even if the pair is separated by interplanetary distances.



1935

Schrödinger's Cat • *Clifford A. Pickover*

Erwin Rudolf Josef Alexander Schrödinger (1887–1961)

Schrödinger's cat reminds me of a ghost, or maybe a creepy zombie—a creature that appears to be alive and dead at the same time. In 1935, Austrian physicist Erwin Schrödinger published an article on this extraordinary paradox with consequences that are so striking that it continues to mystify and concern scientists to this day.

Schrödinger had been upset about the recently proposed *Copenhagen interpretation of quantum mechanics* that stated, in essence, that a quantum system (e.g. an electron) exists as a cloud of probability until an observation is made. At a higher level, it seemed to suggest that it is meaningless to ask precisely what atoms and particles were doing when unobserved; in some sense, reality is created by the observer. Before being observed, the system takes on all possibilities. What could this mean for our everyday lives?

Imagine that a live cat is placed in a box with a radioactive source, a Geiger counter, and a sealed glass flask containing deadly poison. When a radioactive decay event occurs, the Geiger counter measures the event, triggering a mechanism that releases the hammer that shatters the flask and releases the poison that kills the cat. Imagine that quantum theory predicts a 50 percent probability that one decay particle is emitted each hour. After an hour, there is an equal probability that the cat is alive or dead. According to some flavors of the Copenhagen interpretation, the cat seemed to be both alive and dead—a mixture of two states that is called a superposition of states. Some theorists suggested that if you open the box, the very act of observation "collapses the superposition" making the cat either alive or dead.

Schrödinger said that his experiment demonstrated the invalidity of the

Copenhagen interpretation, and Albert Einstein agreed. Many questions spun from this thought experiment: What is considered to be a valid observer? The Geiger counter? A fly? Could the cat observe itself and so collapse its own state? What does the experiment really say about the nature of reality?

SEE ALSO Radioactivity (1896), Geiger Counter (1908), Complementarity Principle (1927), EPR Paradox (1935), Parallel Universes (1956).

When the box is opened, the very act of observation may collapse the superposition, making Schrödinger's cat either alive or dead. Here, Schrödinger's cat thankfully emerges alive.

1936

Turing Machines • *Clifford A. Pickover*

Alan Turing (1912–1954)

Alan Turing was a brilliant mathematician and computer theorist who was forced to become a human guinea pig and subjected to drug experiments to "reverse" his homosexuality. This persecution occurred despite the fact that his code-breaking work helped shorten World War II and led to his award of the Order of the British Empire.

When Turing had called the police to investigate a burglary at his home in England, a homophobic police officer suspected that Turing was homosexual. Turing was forced to either go to jail for a year or take experimental drug therapy. To avoid imprisonment, he agreed to be injected with estrogen hormone for a year. His death at age 42, two years after his arrest, was a shock to his friends and family. Turing was found in bed. The autopsy indicated cyanide poisoning. Perhaps he had committed suicide, but to this day we are not certain.

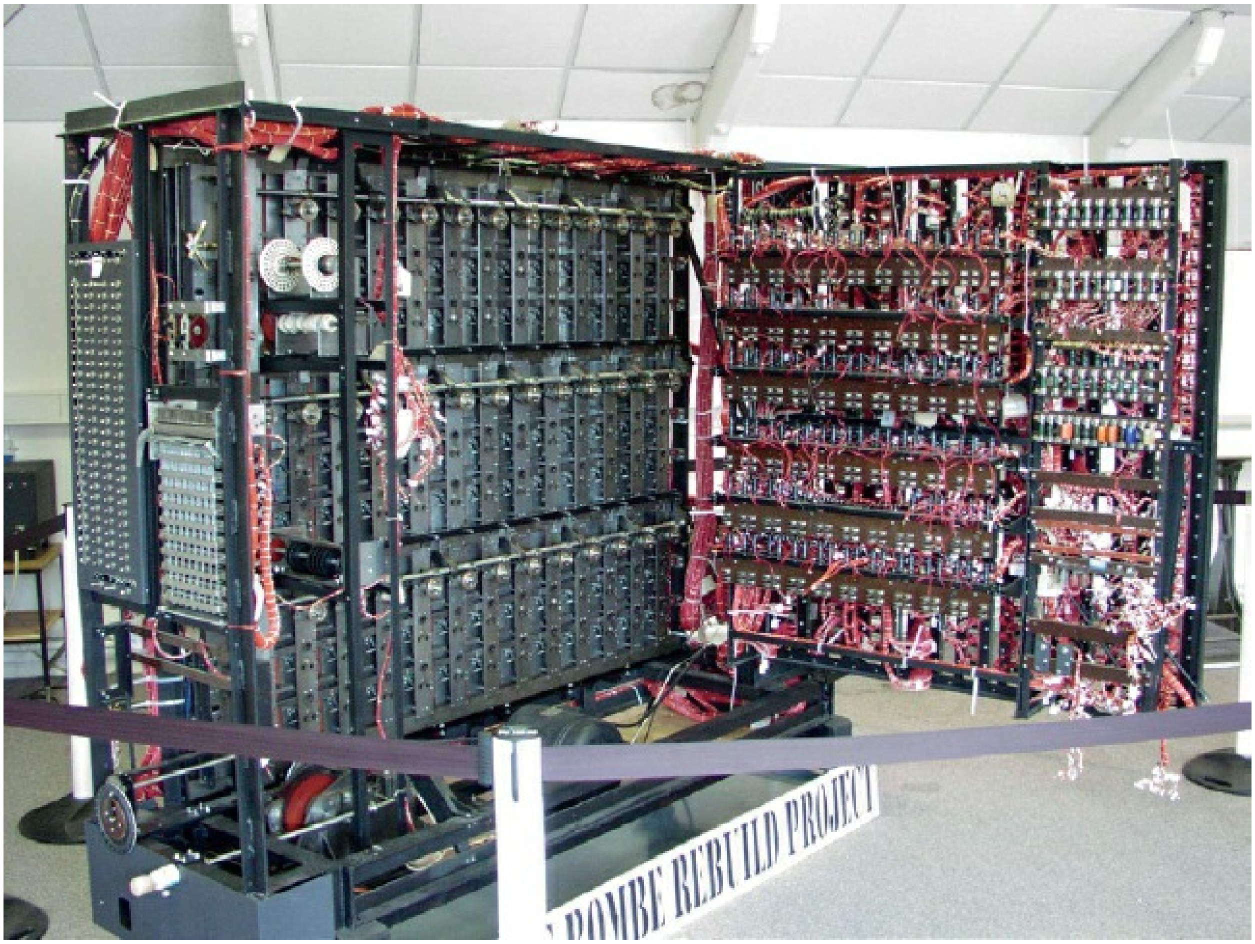
Many historians consider Turing to be the "father of modern computer science." In his landmark paper, "On Computable Numbers, with an Application to the Entscheidungs Problem" (written in 1936), he proved that Turing machines (abstract symbol-manipulating devices) would be capable of performing any conceivable mathematical problem that is represented as an algorithm. Turing machines help scientists better understand the limits of computation.

Turing is also the originator of the Turing test, which caused scientists to think more clearly about what it means to call a machine "intelligent" and whether machines may one day "think." Turing believed that machines would eventually be able to pass his test by demonstrating they could converse with people in such a natural way that people could not tell if they were talking to a machine or a human.

In 1939, Turing invented an electromechanical machine that could help break the Nazi codes produced by their Enigma code machine. Turing's machine, called the "Bombe," was enhanced by mathematician Gordon Welchman, and it became the main tool for deciphering Enigma communications.

SEE ALSO ENIAC (1946), Information Theory (1948), Public-Key Cryptography (1977).

A replica of a Bombe machine. Alan Turing invented this electromechanical device to help break the Nazi codes produced by their Enigma code machine.



1937

Cellular Respiration • *Derek B. Lowe*

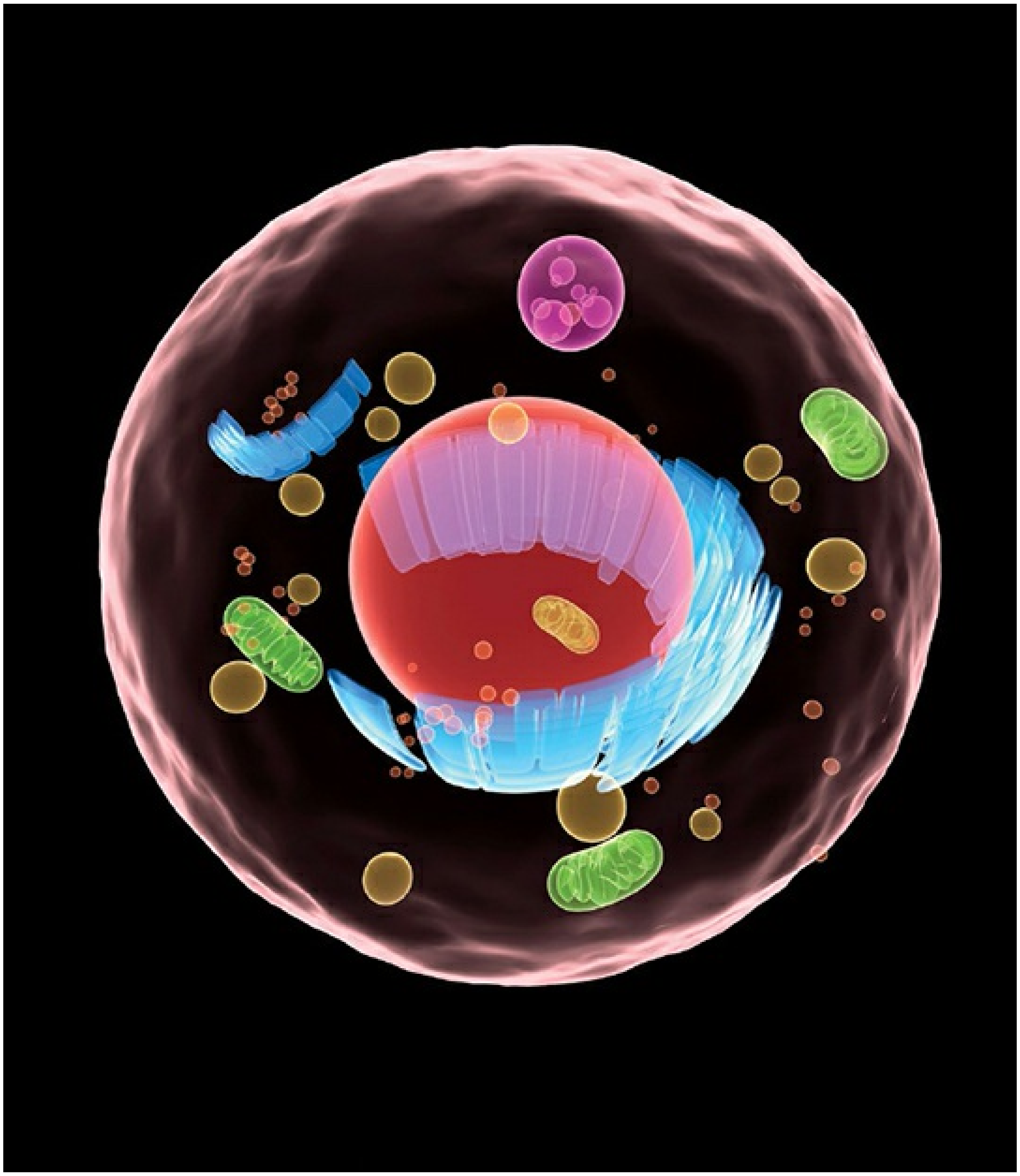
Otto Fritz Meyerhof (1884–1951), **Albert Szent-Györgyi** (1893–1986), **Karl Lohmann** (1898–1978), **Fritz Albert Lipmann** (1899–1986), **Hans Adolf Krebs** (1900–1981), **Paul Delos Boyer** (1918–2018), **Peter Mitchell** (1920–1992), **John Ernest Walker** (b. 1941)

Every living creature needs energy, and they all use the same molecule to carry it: adenosine triphosphate (ATP), discovered in 1929 by German chemist Karl Lohmann, working with Otto Fritz Myerhof. ATP has a phosphate bond that requires a good deal of energy to form, energy that it gives back when that bond is cleaved. The molecule serves as a storable form of power that is ready on demand, an idea proposed by German-American biochemist Fritz Albert Lipmann in 1941. Throughout your body, untold billions of adenosine diphosphates and triphosphates are shuttling back and forth, providing chemical energy like so many battery packs to all sorts of proteins. The ATP-binding pockets built into them are a standardized motif that shows up over and over.

An enzyme called *ATP synthase*—discovered by British biochemist Peter Mitchell, and further explained by the American and British biochemists Paul Boyer and John Walker—allows cells to produce ATP at all times in specialized structures called *mitochondria*. These resemble bacteria, and it's no accident—mitochondria appear to have been bacteria at some point in the distant evolutionary past, moving into early cells and making a home. They're now specialized ATP factories. The first part of their chemistry was worked out in 1937 by German-born British biochemist Hans Adolf Krebs, building on the work of Hungarian physiologist Albert Szent-Györgyi (of vitamin C fame). It's a cycle of reactions starting with citric acid, which is generated again in the last step and sent around for more. Along the way, the two-carbon building block acetate (produced by breaking down carbohydrates and lipids) gets consumed, and carbon dioxide is released. The products of the Krebs cycle go straight into another series of enzyme reactions (called oxidative phosphorylation), which produce ATP while using up oxygen. This is where the food you eat and the oxygen you breathe end up, and where the carbon dioxide you exhale is made: in the nonstop furnaces of the mitochondria.

SEE ALSO Internal Combustion Engine (1908), Photosynthesis (1947), Endosymbiont theory (1967).

The mitochondria are the green ovals in this computer-generated model of the main structures in a typical cell. In muscle cells, mitochondria are more numerous.



1937

Superfluids • *Clifford A. Pickover*

Pyotr Leonidovich Kapitsa (1894–1984), **Fritz Wolfgang London** (1900–1954), **John “Jack” Frank Allen** (1908–2001), **Donald Misener** (1911–1996)

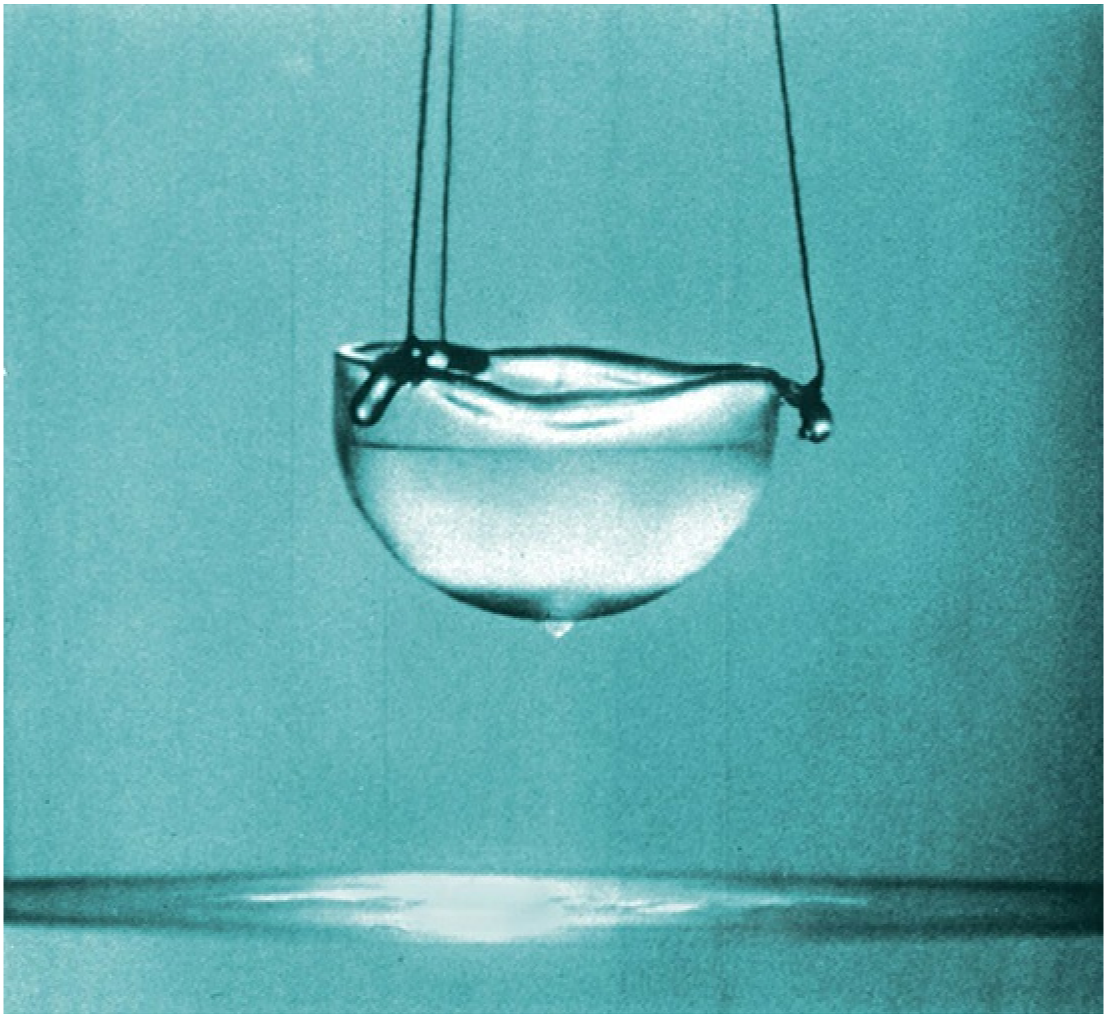
Like some living, creeping liquid out of a science-fiction movie, the eerie behavior of superfluids has intrigued physicists for decades. When liquid helium in a superfluid state is placed in a container, it climbs up the walls and leaves the container. Additionally, the superfluid remains motionless when its container is spun. It seems to seek out and penetrate microscopic cracks and pores, making traditionally adequate containers leaky for superfluids. Place your cup of coffee—with the liquid spinning in the cup—on the table, and a few minutes later the coffee is still. If you did this with superfluid helium, and your ancestors came back in a thousand years to view the cup, the superfluid might still be spinning.

Superfluidity is seen in several substances, but often studied in helium-4—the common, naturally occurring isotope of helium containing two protons, two neutrons, and two electrons. Below an extremely cold critical temperature called the lambda temperature (−455.49 ºF, 2.17 K), this liquid helium-4 suddenly attains the ability to flow without apparent friction and achieves a thermal conductivity that is millions of times the conductivity of normal liquid helium and much greater than the best metal conductors. The term *helium I* refers to the liquid above 2.17 K, and *helium II* refers to the liquid below this temperature.

Superfluidity was discovered by physicists Pyotr Kapitsa, John F. Allen, and Don Misener in 1937. In 1938, Fritz London suggested that liquid helium beneath the lambda point temperature is composed of two parts, a normal fluid with characteristics of helium 1 and a superfluid (with a viscosity value essentially equal to 0). The transition from ordinary fluid to superfluid occurs when the constituent atoms begin to occupy the same quantum state, and their quantum wave functions overlap. As in the Bose-Einstein Condensate, the atoms lose their individual identities and behave as one large smeared entity. Because the superfluid has no internal viscosity, a vortex formed within the fluid continues to spin essentially forever.

SEE ALSO Bernoulli's Law of Fluid Dynamics (1738), Superconductivity (1911) Heisenberg Uncertainty Principle (1927).

Frame from Alfred Leitner's 1963 movie Liquid Helium, Superfluid. The liquid helium is in the superfluid phase as a thin film creeps up the inside wall of the suspended cup and down on the outside to form a droplet at the bottom.



1938

Nuclear Magnetic Resonance • *Clifford A. Pickover*

Isidor Isaac Rabi (1898–1988), **Felix Bloch** (1905–1983), **Edward Mills Purcell** (1912–1997), **Richard Robert Ernst** (b. 1933), **Raymond Vahan Damadian** (b. 1936)

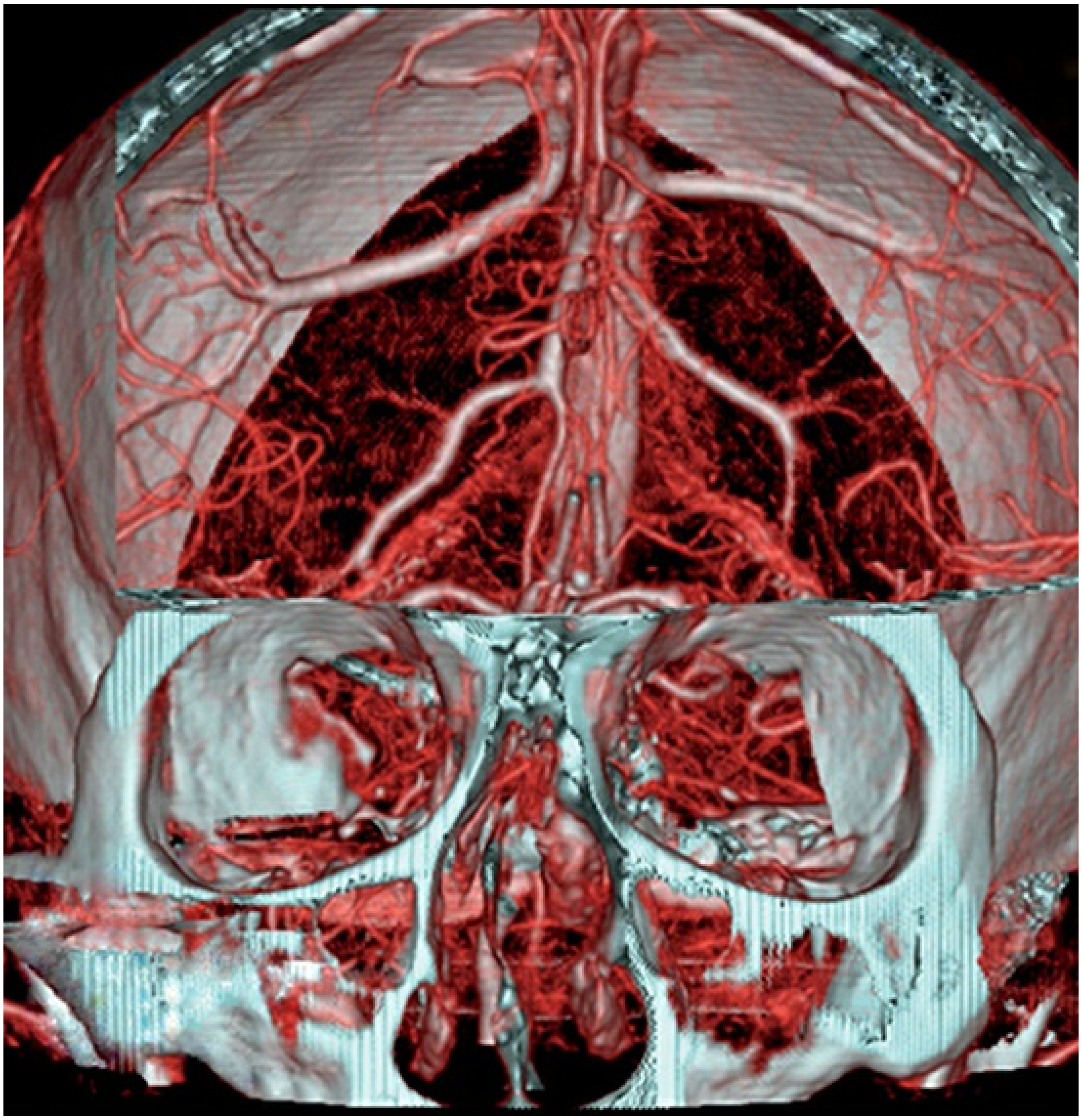
"Scientific research requires powerful tools for elucidating the secrets of nature," writes Nobel Laureate Richard Ernst. "Nuclear Magnetic Resonance (NMR) has proved to be one of the most informative tools of science with applications to nearly all fields from solid state physics, to material science, . . . and even to psychology, trying to understand the functioning of the human brain."

If an atomic nucleus has at least one neutron or proton unpaired, the nucleus may act like a tiny magnet. When an external magnetic field is applied, it exerts a force that can be visualized as causing the nuclei to precess, or wobble, like a spinning top. The potential energy difference between nuclear spin states can be made larger by increasing the external magnetic field. After turning on this static external magnetic field, a radio-frequency (RF) signal of the proper frequency is introduced that can induce transitions between spin states, and thus some of the spins are placed in their higher-energy states. If the RF signal is turned off, the spins relax back to the lower state and produce an RF signal at the *resonant* frequency associated with the spin flip. These NMR signals yield information beyond the specific nuclei present in a sample, because the signals are modified by the immediate chemical environment. Thus, NMR studies can yield a wealth of molecular information.

NMR was first described in 1937 by physicist Isidor Rabi. In 1945, physicists Felix Bloch, Edward Purcell, and colleagues refined the technique. In 1966, Richard Ernst further developed Fourier transform (FT) spectroscopy and showed how RF pulses could be used to create a spectrum of NMR signals as a function of frequency. In 1971, physician Raymond Damadian showed that the hydrogen relaxation rates of water could be different in normal and malignant cells, opening the possibility of using NMR for medical diagnosis. In the early 1980s, NMR methods started to be used in magnetic resonance imaging (MRI) to characterize the nuclear magnet moments of ordinary hydrogen nuclei of soft tissues of the body.

SEE ALSO X-rays (1895), Atomic Nucleus (1911), Superconductivity (1911).

An actual MRI/MRA (magnetic resonance angiogram) of the brain vasculature (arteries). This kind of MRI study is often used to reveal brain aneurysms.



1941

Doped Silicon • *Marshall Brain*

John Robert Woodyard (1904–1981)

If we had to pick a substance that engineers have used to impart the biggest effect on humanity, what might that substance be? Maybe it is gunpowder, which engineers use in guns, cannons, and bombs. By killing untold millions of people, gunpowder has certainly had an effect, although not a particularly happy one. Maybe it is uranium, which engineers use in both nuclear bombs and nuclear power plants. Or asphalt, which billions of people use every day for transportation, or the concrete used in so many structures. What about gasoline, powering most of our vehicles?

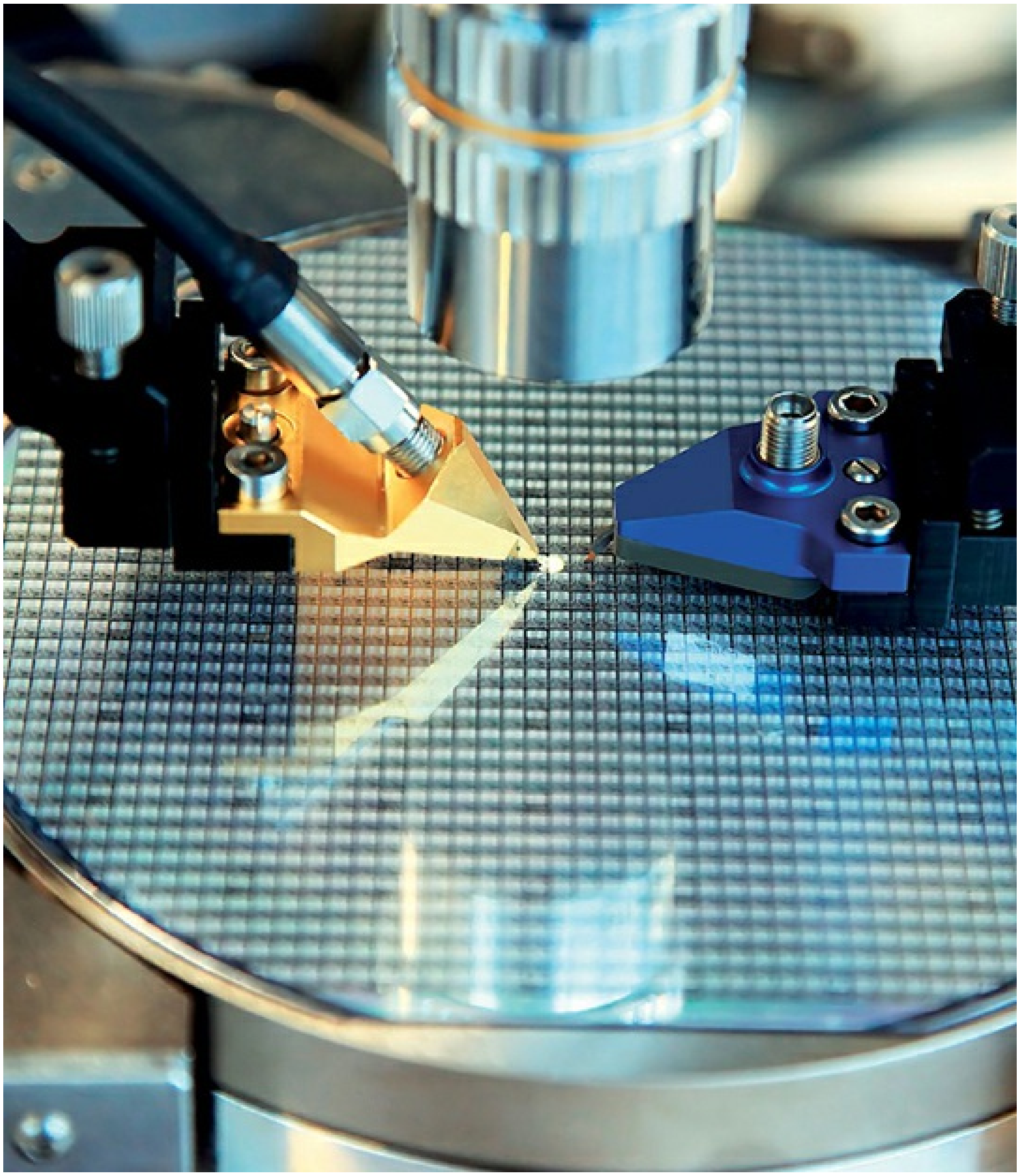
The award for the most influential material might best go to . . . drumroll please . . . doped silicon. Doped silicon was developed by physicist John Robert Woodyard while in the service of the Sperry Gyroscope Company in 1941. This material, the foundation of the transistor, has transformed our society in a thousand different ways. Look around you and count how many objects use computers in one form or another. Think about how much time you spend using a laptop, tablet, or smart phone. Think about the billions of computers connected to the Internet.

And think about where we are headed. The “Internet of things” is the next big thing. It is predicted that, in just a decade or two, there will be 100 trillion objects connected on the Internet. They will be everywhere: home appliances, cameras, sensors, cars, tracking devices, drones, our homes and their security systems. Doped silicon has made computers so inexpensive, so power-efficient, and so intelligent, that computers are embedding in everything and connecting together on the Internet. And then there are robots, which will be arriving in massive numbers in the not-too-distant future.

The doping process is conceptually simple. Start with a pure silicon crystal. Add various dopants, like boron to create an area of holes, or phosphorous to create an area with free electrons. Combining these doped areas properly, an engineer can create diodes and transistors. With transistors, engineers can create amplifiers, receivers, and computers. Our computer and electronics industries are built on top of doped silicon.

SEE ALSO Transistor (1947), Integrated Circuit (1958), ARPANET (1969).

A silicon wafer, pictured here, is a thin slice of semiconductor material.



1942

Energy from the Nucleus • *Clifford A. Pickover*

Lise Meitner (1878–1968), **Albert Einstein** (1879–1955), **Leó Szilárd** (1898–1964), **Enrico Fermi** (1901–1954), **Otto Robert Frisch** (1904–1979)

Nuclear fission is a process in which the nucleus of an atom, such as uranium, splits into smaller parts, often producing free neutrons, lighter nuclei, and a large release of energy. A chain reaction takes place when the neutrons fly off and split other uranium atoms, and the process continues. A nuclear reactor, used to produce energy, makes use of the process that is moderated so that it releases energy at a controlled rate. A nuclear weapon uses the process in a rapid, uncontrolled rate. The products of nuclear fission are themselves often radioactive and thus may lead to nuclear waste problems associated with nuclear reactors.

In 1942, in a squash court beneath the stadium at the University of Chicago, physicist Enrico Fermi and his colleagues produced a controlled nuclear chain reaction using uranium. Fermi had relied on the 1939 work of physicists Lise Meitner and Otto Frisch, who showed how the uranium nucleus breaks into two pieces, unleashing tremendous energy. In the 1942 experiment, metal rods absorbed the neutrons, allowing Fermi to control the rate of reaction. Author Alan Weismann explains, “Less than three years later, in a New Mexico desert, they did just the opposite. The nuclear reaction this time [which included plutonium] was intended to go completely out of control. Immense energy was released, and within a month, the act was repeated twice, over two Japanese cities. . . . Ever since, the human race has been simultaneously terrified and fascinated by the double deadliness of nuclear fission: fantastic destruction followed by slow torture.”

The Manhattan Project, led by the U.S., was the codename for a project conducted during World War II to develop the first atomic bomb. Physicist Leó Szilárd had been so concerned about German scientists creating nuclear weapons that he approached Albert Einstein to obtain his signature for a letter sent to President Roosevelt in 1939, alerting him to this danger. Note that a second kind of nuclear weapon (an “H-bomb”) uses nuclear fusion reactions.

SEE ALSO Radioactivity (1896), $E = mc^2$ (1905), Nucleus (1911), Little Boy Atomic Bomb (1945).

LEFT: *Lise Meitner was part of the team that discovered nuclear fission (1906 photo).* RIGHT: *Calutron (mass spectrometer) operators in the Y-12 plant at Oak Ridge, Tennessee, during World War II. The calutrons were used to refine uranium ore into fissile material. Workers toiled in secrecy during the Manhattan Project effort to construct an atomic explosive.*

1945

Little Boy Atomic Bomb • *Clifford A. Pickover*

J. Robert Oppenheimer (1904–1967), **Paul Warfield Tibbets**, **Jr.** (1915–2007)

On July 16, 1945, American physicist J. Robert Oppenheimer watched the first detonation of an atomic bomb in the New Mexico deserts, and he recalled a line from the *Bhagavad Gita*, "Now I become Death, the destroyer of worlds." Oppenheimer was the scientific director of the Manhattan Project, the World War II effort to develop the first nuclear weapon.

Nuclear weapons are exploded as a result of nuclear fission, nuclear fusion, or a combination of both processes. Atomic bombs generally rely on *nuclear fission* in which certain isotopes of uranium or plutonium split into lighter atoms, releasing neutrons and energy in a chain reaction. Thermonuclear bombs (or hydrogen bombs) rely on *fusion* for a portion of their destructive power. In particular, at very high temperatures, isotopes of hydrogen combine to form heavier elements and release energy. These high temperatures are achieved with a fission bomb to compress and heat fusion fuel.

Little Boy was the name of the atomic bomb dropped on Hiroshima, Japan on August 6, 1945, by the bomber plane *Enola Gay*, piloted by Colonel Paul Tibbets. Little Boy was about 9.8 feet long (3.0 meters) and contained 140 pounds (64 kilograms) of enriched uranium. After release from the plane, four radar altimeters were used to detect the altitude of the bomb. For greatest destructive power, the bomb was to explode at an altitude of 1,900 feet (580 meters). When any two of the four altimeters sensed the correct height, a cordite charge was to explode in the bomb, firing one mass of uranium-235 down a cylinder into another mass to create a self-sustaining nuclear reaction. After the explosion, Tibbets recalled the “awful cloud . . . boiling up, mushrooming terrible and incredibly tall.” Over a period of time, as many as 140,000 people were killed—roughly half due the immediate blast and the other half due to gradual effects of the radiation. Oppenheimer later noted, “The deep things in science are not found because they are useful; they are found because it was possible to find them.”

SEE ALSO Von Guericke’s Electrostatic Generator (1660), Radioactivity (1896), Energy from the Nucleus (1942).

Little Boy on trailer cradle in pit, August 1945. Little Boy was about 9.8 feet (3.0 meters) long. Over a period of time, Little Boy may have killed as many as 140,000 people.

1945

Uranium Enrichment • *Marshall Brain*

Imagine the following situation faced by engineers working on the Manhattan Project in 1942. The uranium that comes out of the ground is almost entirely U-238. But mixed in with the U-238 atoms is the occasional U-235 atom (less than 1 percent). The U-235 atoms are what engineers need to build a nuclear bomb. How is it possible to separate the U-235 atoms from the U-238 atoms?

There are lots of processes that engineers use in factories to separate one thing from another. Oil refineries use different boiling and condensation temperatures. Quarries use sieves to separate different sizes of gravel. If salt and sand mix together, water can chemically dissolve the salt to separate it. But separating U-235 from U-238 is difficult because the atoms are nearly identical.

People came up with many different ideas for performing the separation: thermal, magnetic, centrifuge, etc. The method they settled on as the best means of separation at the time is called gaseous diffusion and it involves two steps: Turn solid uranium into a gas called uranium hexafluoride, and let the gas diffuse though hundreds of micro-porous membranes, which have a slight preference for letting U-235 atoms through instead of U-238 atoms.

While this sounds simple, engineering a structure to perform the operation reliably turned out to be a gigantic engineering challenge. The K-25 building —the first full-scale gaseous diffusion plant, at Oak Ridge, Tennessee—came online in 1945, cost $500 million at the time ($8 billion today) and used a noticeable percentage of the nation’s electricity. The building was enormous —one of the largest in the world, with something like fifty enclosed acres holding thousands of diffusion chambers along with their pumps, seals, valves, temperature controls, etc. One of the biggest problems was the highly corrosive nature of uranium hexafluoride. Newly developed materials like

Teflon helped block its action.

With an unprecedented level of secrecy and a speed that boggles the mind, engineers built K-25 (and other plants) and brought them online to purify the uranium for the first atomic bombs. After World II, the gaseous diffusion process kept purifying uranium until it was replaced by more efficient centrifuges.

SEE ALSO Atomic Nucleus (1911), Energy from the Nucleus (1942), Little Boy Atomic Bomb (1945).

Gas centrifuges used to produce enriched uranium. This photograph is of the US gas centrifuge plant in Piketon, Ohio, from 1984.

1946

ENIAC • *Clifford A. Pickover*

John Mauchly (1907–1980), **J. Presper Eckert** (1919–1995)

ENIAC, short for Electronic Numerical Integrator and Computer, was built at the University of Pennsylvania by American scientists John Mauchly and J. Presper Eckert. This device was the first electronic, reprogrammable, digital computer that could be used to solve a large range of computing problems. The original purpose of ENIAC was to calculate artillery firing tables for the U.S. Army; however, its first important application involved the design of the hydrogen bomb.

ENIAC was unveiled in 1946, having cost nearly $500,000, and it was in nearly continuous use until it was turned off on October 2, 1955. The machine contained more than 17,000 vacuum tubes and around 5 million hand-soldered joints. An IBM card reader and card punch machine were used for input and output. In 1997, a team of engineering students led by Professor Jan Van der Spiegel created a "replica" of the 30-ton ENIAC on a single integrated circuit!

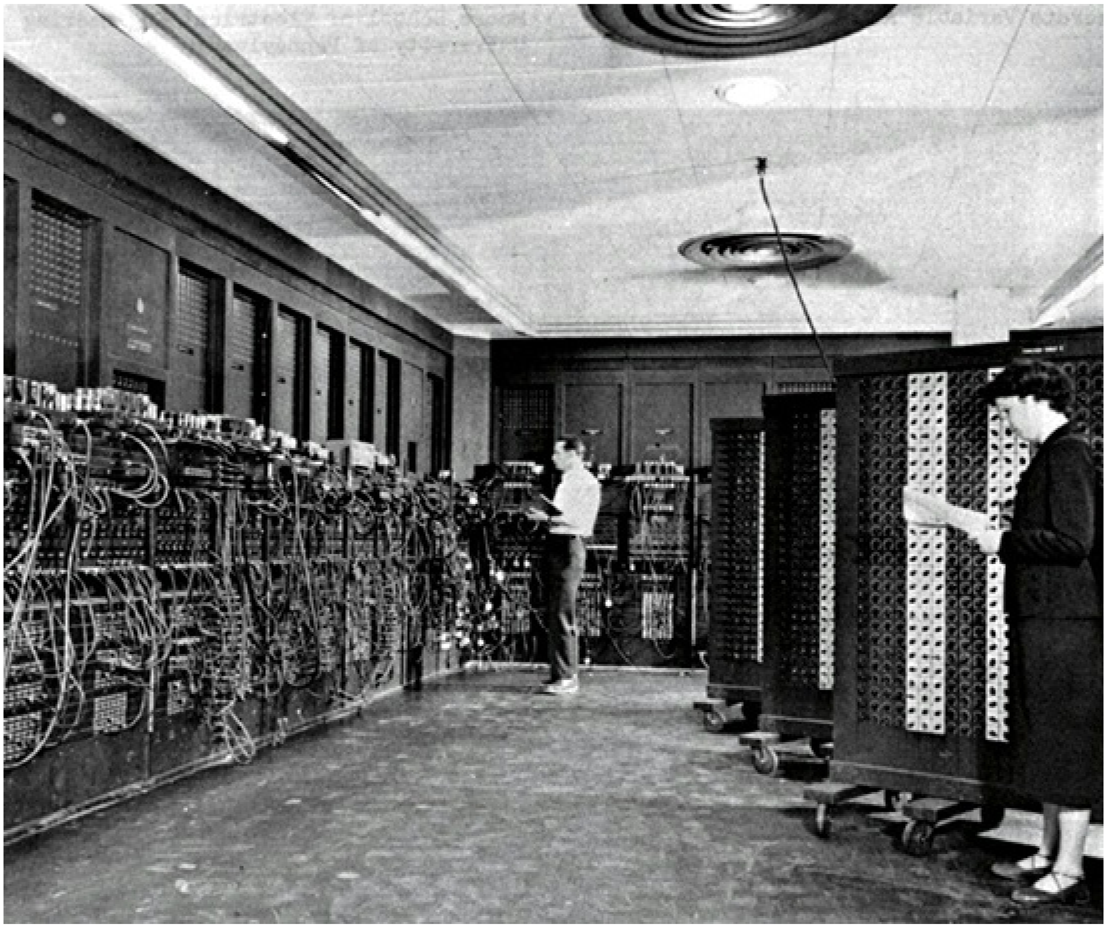
Other important electrical computing machines of the 1930s and 1940s include the American Atanasoff-Berry Computer (demonstrated in December, 1939), the German Z3 (demonstrated in May, 1941), and the British Colossus computer (demonstrated in 1943); however, these machines were either not fully electronic or not general purpose.

The authors of the ENIAC patent (No. 3,120,606; filed in 1947) write, "With the advent of everyday use of elaborate calculations, speed has become paramount to such a high degree that there is no machine on the market today capable of satisfying the full demand of modern computational methods. . . . The present invention is intended to reduce to seconds such lengthy computations. . . .”

Today, computer use has invaded most areas of mathematics, including numerical analysis, number theory, and probability theory. Mathematicians, of course, increasingly use computers in their research and in their teaching, sometimes using computer graphics to gain insight. Famous mathematical proofs have been done with the aid of the computer.

SEE ALSO Antikythera Mechanism (c. 125 BCE) Slide Rule (1621), Babbage Mechanical Computer (1822), Turing Machines (1936), Transistor (1947).

U.S. Army photo of ENIAC, the first electronic, reprogrammable, digital computer that could be used to solve a large range of computing problems. Its first important application involved the design of the hydrogen bomb.



1946

Stellar Nucleosynthesis • *Clifford A. Pickover*

Fred Hoyle (1915–2001)

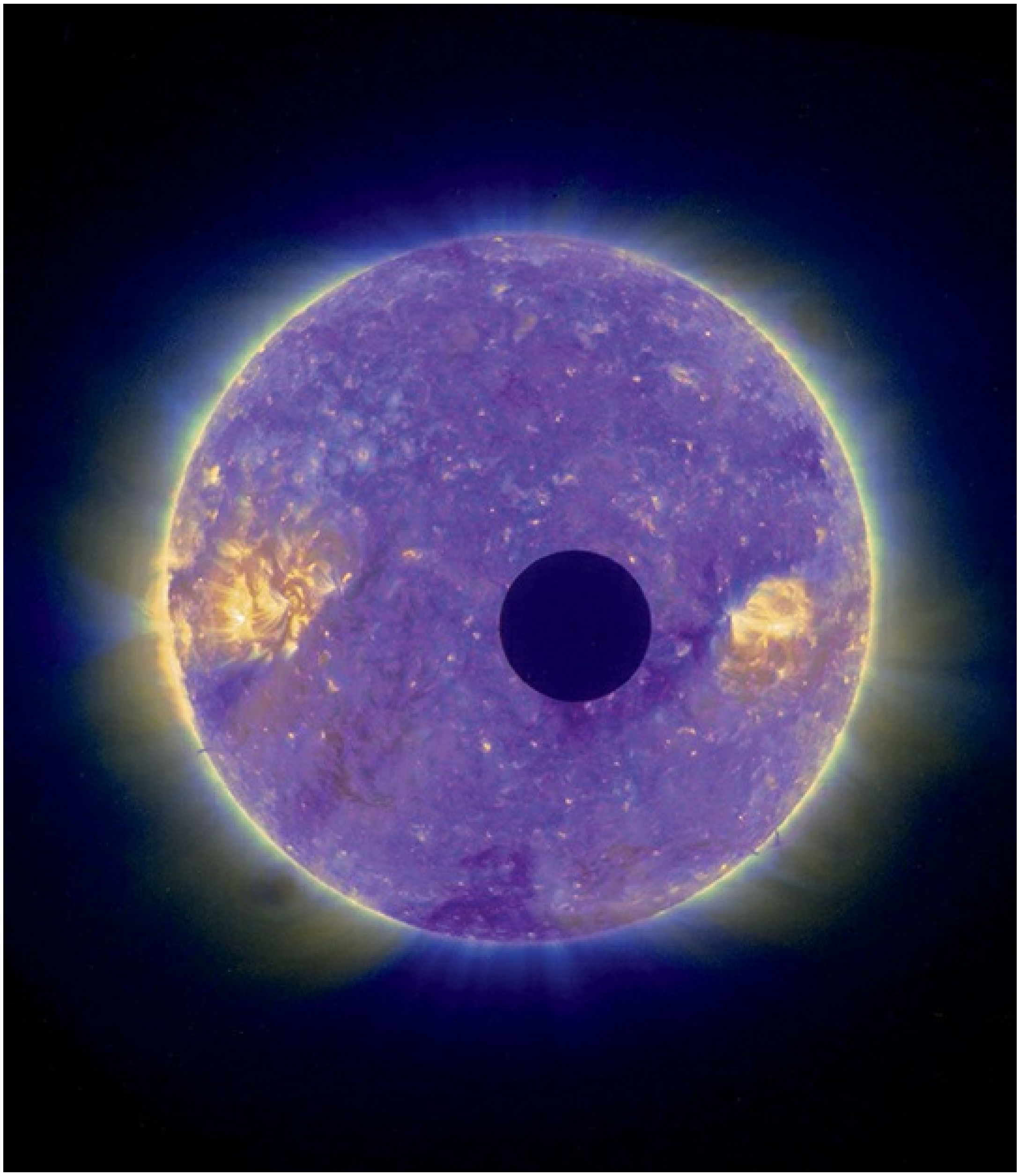
“Be humble for you are made of dung. Be noble for you are made of stars.” This old Serbian proverb serves to remind us today that all the elements heavier than hydrogen and helium would not exist in any substantial amounts in the universe were it not for their production in stars that eventually died and exploded and scattered the elements into the universe. Although light elements such as helium and hydrogen were created in the first few minutes of the Big Bang, the subsequent nucleosynthesis (atomic-nucleus creation) of the heavier elements required massive stars with their nuclear fusion reactions over long periods of time. Supernova explosions rapidly created even heavier elements due to an intense burst of nuclear reactions during the explosion of the core of the star. Very heavy elements, like gold and lead, are produced in the extremely high temperatures and neutron flux of a supernova explosion. The next time you look at the golden ring on a friend’s finger, think of supernova explosions in massive stars.

Pioneering theoretical work into the mechanism with which heavy nuclei were created in stars was performed in 1946 by astronomer Fred Hoyle who showed how very hot nuclei could assemble into iron.

As I write this entry, I touch a saber-tooth tiger skull in my office. Without stars, there could be no skulls. As mentioned, most elements, like calcium in bones, were first cooked in stars and then blown into space when the stars died. Without stars, the tiger racing across the savanna fades away, ghostlike. There are no iron atoms for its blood, no oxygen for it to breathe, no carbon for its proteins and DNA. The atoms created in the dying ancient stars were blown across vast distances and eventually formed the elements in the planets that coalesced around our Sun. Without these supernova explosions, there are no mist-covered swamps, computer chips, trilobites, Mozarts, or the tears of a little girl. Without exploding stars, perhaps there could be a heaven, but there is certainly no Earth.

SEE ALSO Sun-Centered Universe (1543), $E = mc^2$ (1905), Atomic Nucleus (1911).

The Moon passing in front of the Sun, captured by NASA's STEREO-B spacecraft on February 25, 2007, in four wavelengths of extreme ultraviolet light. Because the satellite is farther from the Sun than the Earth, the Moon appears smaller than usual.



1947

Hologram • *Clifford A. Pickover*

Dennis Gabor (1900–1979)

Holography, the process by which a three-dimensional image can be recorded and later reproduced, was invented in 1947 by physicist Dennis Gabor. In his Nobel Prize acceptance speech for the invention, he said of holography, “I need not write down a single equation or show an abstract graph. One can, of course, introduce almost any amount of mathematics into holography, but the essentials can be explained and understood from physical arguments.”

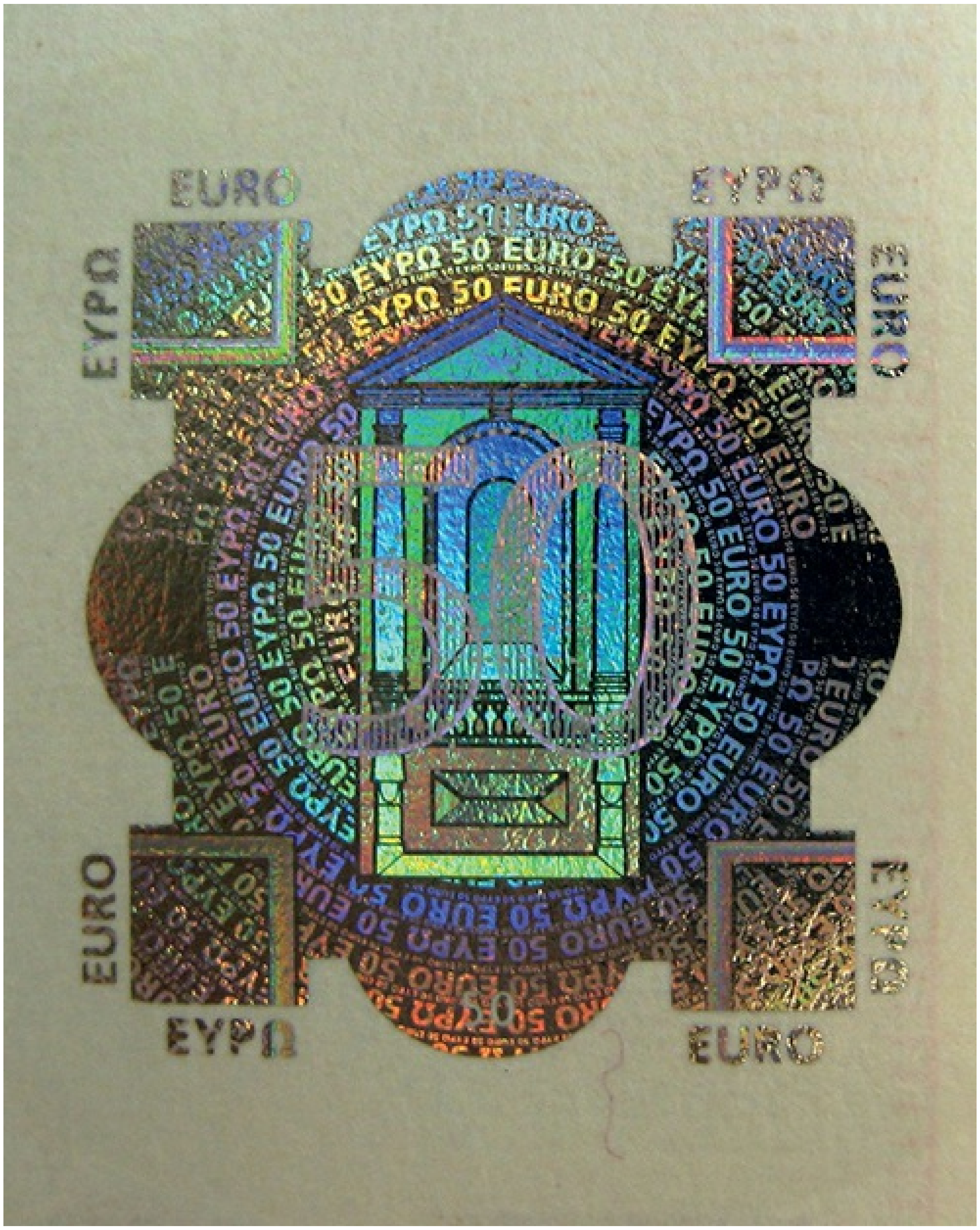
Consider an object such as a pretty peach. Holograms can be stored on photographic film as a record of the peach from many viewpoints. To produce a transmission hologram, a beam-splitter is used to divide the laser light into a reference beam and an object beam. The reference beam does not interact with the peach and is directed toward the recording film with a mirror. The object beam is aimed at the peach. The light reflected off the peach meets the reference beam to create an interference pattern in the film. This pattern of stripes and whorls is totally unrecognizable. After the film is developed, a 3D image of the peach can be reconstructed in space by directing light toward the hologram at the same angle used for the reference beam. The finely spaced fringes on the hologram film act to diffract, or deflect, the light to form the 3D image.

“Upon seeing your first hologram,” write physicists Joseph Kasper and Steven Feller, “you are certain to feel puzzlement and disbelief. You may place your hand where the scene apparently lies, only to find nothing tangible is there.”

Transmission holograms employ light shining through the developed film from behind, and *reflection holograms* make use of light shining on the film with the light source in front of the film. Some holograms require laser light for viewing, while rainbow holograms (such as those with a reflective coating commonly seen on credit cards) can be viewed without the use of lasers. Holography can also be used to optically store large amounts of data.

SEE ALSO Newton's Prism (1672), Wave Nature of Light (1801), Laser (1960).

The hologram on the 50 euro banknote. Security holograms are very difficult to forge.


EURO
EYPΩ
EYPΩ 50 EURO
EURO
EYPΩ

1947

Photosynthesis • *Derek B. Lowe*

Melvin Calvin (1911–1997), **Samuel Goodnow Wildman** (1912–2004), **Andrew Alm Benson** (1917–2015), **James Alan Bassham** (1922–2012)

Photosynthesis is the quiet, unnoticed chemistry that is keeping everyone and everything on Earth alive. Our planet's atmosphere didn't even have much oxygen until photosynthetic microbes began cranking it out as a waste product (gradually killing off the planet's original microbial inhabitants or driving them into hiding). Photosynthesis not only produces the oxygen we breathe, but it also helps regulate the amount of carbon dioxide in the air. And as if making our atmosphere breathable were not enough, photosynthesis underpins the global food chain for almost every living organism, including humankind.

The strange thing is, the whole process depends on what appears to be one of the clunkiest enzymes ever seen. In 1947, Samuel Goodnow Wildman reported his discovery of a large, extremely abundant enzyme in spinach leaves that turned out to be a key player. Referred to by the laboratory nickname *Rubisco*, which is short for *ribulose biscarboxylase oxygenase* (and no wonder), it is an essential part of the Calvin cycle—the plant world's equivalent of the Krebs cycle of cellular respiration—discovered by American biochemist Melvin Calvin, working with compatriots James Alan Bassham, a chemist, and Andrew Alm Benson, a biologist. (Instead of mitochondria, plant cells have other ancient interlopers called chloroplasts to perform this work.)

Rubisco, probably the most abundant protein on Earth, can account for up to half the protein weight of a plant. The reason there's so much of it is that it's an incredibly slow enzyme. Instead of zipping through thousands of molecular changes per second, it processes *three*. It may be that this bizarrely low rate is a trade-off against its ability to tell carbon dioxide from oxygen; this is still an open question. After several billion years of evolutionary pressure, odds are that there must be good reasons for such an important enzyme to be so strange, but many research groups are putting that to the test by seeing what happens if they try to improve it for use in artificial photosynthesis.

SEE ALSO Nitrogen Cycle and Plant Chemistry (1837), Cellular Respiration (1937), Green Revolution (1961).

The green chloroplasts—where the Rubisco enzyme does its slow, strange work—are clearly visible inside these plant cells.

1947

Transistor • *Clifford A. Pickover*

Julius Edgar Lilienfeld (1882–1963), **John Bardeen** (1908–1991), **Walter Houser Brattain** (1902–1987), **William Bradford Shockley** (1910–1989)

A thousand years from now, when our ancestors reflect upon history, they will mark December 16, 1947 as the start of humankind's Information Age—the day on which Bell Telephone Laboratories physicists John Bardeen and Walter Brattain connected two upper electrodes to a piece of specially treated germanium that sat on a third electrode (a metal plate attached to a voltage source). When a small current was introduced through one of the upper electrodes, another much stronger current flowed through the other two electrodes. The transistor was born.

Given the magnitude of the discovery, Bardeen's reaction was rather sedate. That evening, walking in through the kitchen door of his home, he mumbled to his wife, "We discovered something important today," and he said no more. Their fellow scientist William Shockley understood the device's great potential and also contributed to the knowledge of semiconductors. Later, when Shockley was angered by being left out of the Bell Lab's transistor patent that had only the names of Bardeen and Brattain, he created a better transistor design.

A transistor is a semiconductor device that may be used to amplify or switch electronic signals. The conductivity of a semiconductor material can be controlled by introduction of an electrical signal. Depending on the transistor design, a voltage or current applied to one pair of the transistor's terminals changes the current flowing through another terminal.

Physicists Michael Riordan and Lillian Hoddeson write, “It is hard to imagine any device more crucial to modern life than the microchip and the transistor from which it sprang. Every waking hour, people of the world take their vast benefits for granted—in cellular phones, ATMs, wrist watches, calculators, computers, automobiles, radios, televisions, fax machines, copiers, stoplights, and thousands of electronic devices. Without a doubt, the transistor is the most important artifact of the 20th century and the ‘nerve cell’ of our electronic age.” In the future, fast transistors made from graphene (sheets of carbon atoms) and carbon nanotubes may become practical. Note that, in 1925, physicist Julius Lilienfeld was the first to actually file a patent for an early version of the transistor.

SEE ALSO ENIAC (1946), Integrated Circuit (1958), Quantum Computers (1981).

The Regency TR-1 radio, announced in October 1954, was the first practical transistor radio made in bulk quantities. Shown here is a figure from Richard Koch’s transistor-radio patent. Koch was employed by the company that made the TR-1.

June 30, 1959 R. C. KOCH 2,892,931

TRANSISTOR RADIO APPARATUS

Filed March 25, 1955 2 Sheets-Sheet 1

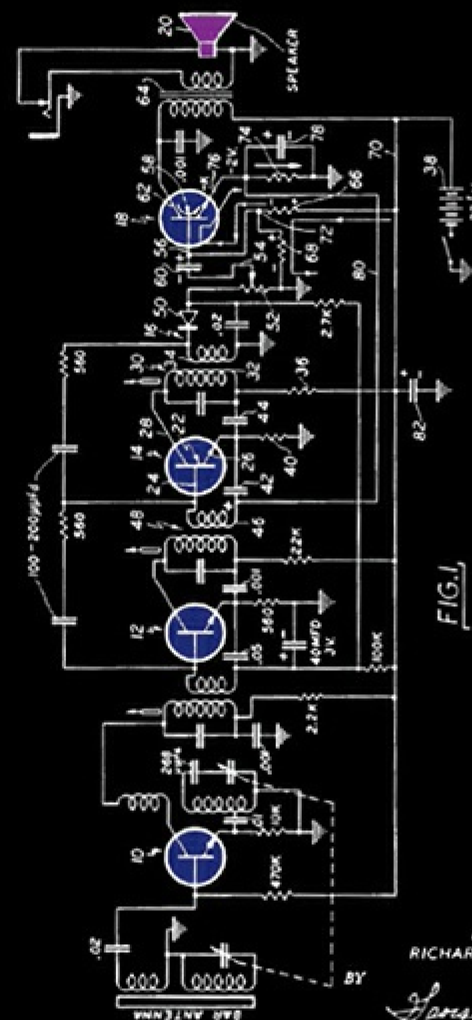


FIG. I

INVENTOR.
RICHARD C. KOCH

BY George R. Gust

ATTORNEY

1948

Information Theory • *Clifford A. Pickover*

Claude Elwood Shannon (1916–2001)

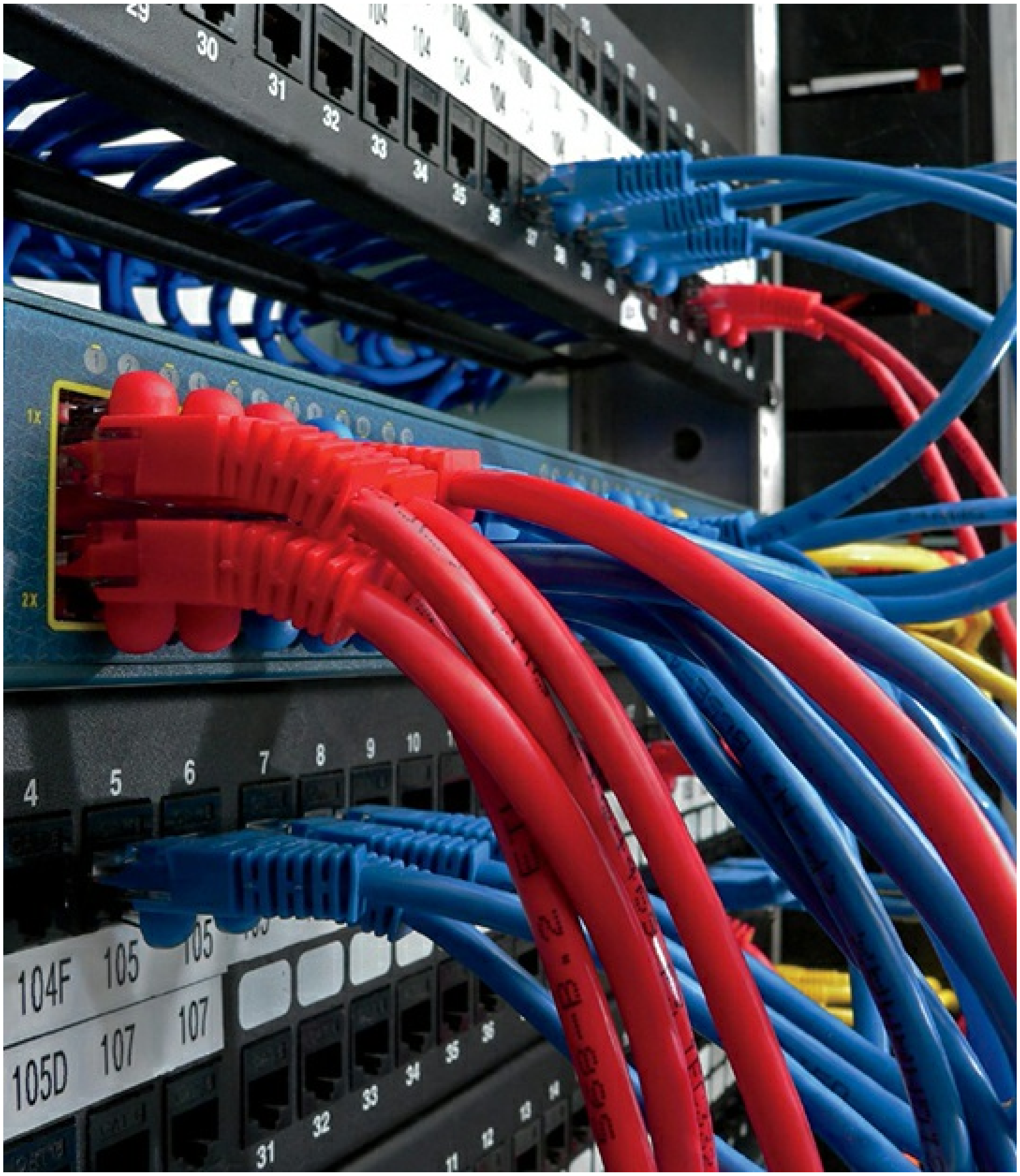
Teenagers watch TV, cruise the Internet, spin their DVDs, and chat endlessly on the phone usually without ever realizing that the foundations for this Information Age were laid by American mathematician Claude Shannon, who in 1948 published “A Mathematical Theory of Communication.” Information theory is a discipline of applied mathematics involving the quantification of data, and it helps scientists understand the capacity of various systems to store, transmit, and process information. Information theory is also concerned with data compression and with methods for reducing noise and error rates to enable as much data as possible to be reliably stored and communicated over a channel. The measure of information, known as information entropy, is usually expressed by the average number of bits needed for storage or communication. Much of the mathematics behind information theory was established by Ludwig Boltzmann and J. Willard Gibbs for the field of thermodynamics. Alan Turing also used similar ideas when breaking of the German Enigma ciphers during World War II.

Information theory affects a diverse array of fields, ranging from mathematics and computer science to neurobiology, linguistics, and black holes. Information theory has practical applications such as breaking codes and recovering from errors due to scratches in movie DVDs. According to a 1953 issue of *Fortune*: “It may be no exaggeration to say that man’s progress in peace, and security in war, depend more on fruitful applications of Information Theory than on physical demonstrations, either in bombs or in power plants, that Einstein’s famous equation works.”

Claude Shannon died in 2001, at the age of 84, after a long struggle with Alzheimer's disease. At one point in his life, he had been an excellent juggler, unicyclist, and chess player. Sadly, due to his affliction, he was unable to observe the Information Age that he helped create.

SEE ALSO Telegraph System (1837), Fiber Optics (1841), Turing Machines (1936), ENIAC (1946).

Information theory helps technologists understand the capacity of various systems to store, transmit, and process information. Information theory has applications in fields ranging from computer science to neurobiology.



30
31
32
33
34
35
36
4
5
6
7
8
9
10
104F
105
105
105D
107
107
31
32
33
34
35
36

1948

Quantum Electrodynamics • *Clifford A. Pickover*

Paul Adrien Maurice Dirac (1902–1984), **Sin-Itiro Tomonaga** (1906–1979), **Richard Phillips Feynman** (1918–1988), **Julian Seymour Schwinger** (1918–1994)

"Quantum electrodynamics (QED) is arguably the most precise theory of natural phenomena ever advanced," writes physicist Brian Greene. "Through quantum electrodynamics, physicists have been able to solidify the role of photons as the 'smallest possible bundles of light' and to reveal their interactions with electrically charged particles such as electrons, in a mathematically complete, predictable and convincing framework." QED mathematically describes interactions of light with matter and also the interactions of charged particles with one another.

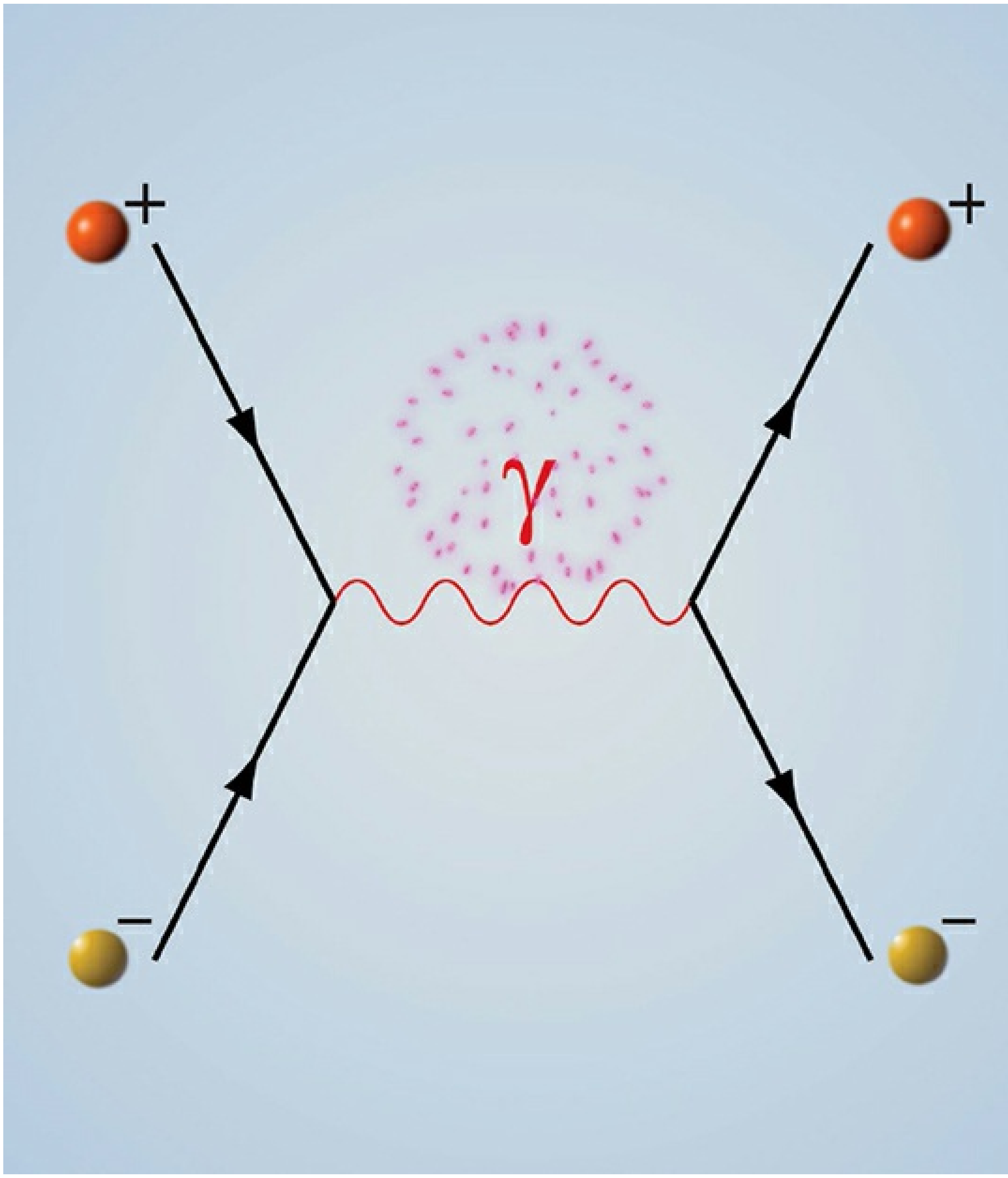
In 1928, the English physicist Paul Dirac established the foundations for QED, and the theory was refined and developed in the late 1940s by physicists Richard P. Feynman, Julian S. Schwinger, and Sin-Itiro Tomonaga. QED relies on the idea that charged particles (such as electrons) interact by emitting and absorbing photons, which are the particles that transmit electromagnetic forces. Interestingly, these photons are "virtual" and cannot be detected, yet they provide the "force" of the interaction as the interacting particles change their speed and direction of travel when absorbing or releasing the energy of a photon. The interactions can be graphically represented and understood through the use of squiggly Feynman diagrams. These drawings also help physicists to calculate the probability that particular interactions take place.

According to QED theory, the greater the number of virtual photons exchanged in an interaction (i.e., a more complex interaction), the less likely is the chance of occurrence of the process. The accuracy of predictions made by QED is astonishing. For example, the predicted strength of the magnetic field carried by an electron is so close to the experimental value, that if you could measure the distance from New York to Los Angles with this accuracy, you would be accurate to within the thickness of a human hair.

QED has served as the launchpad for subsequent theories, such as *quantum chromodynamics*, which began in the early 1960s and involves the strong forces that hold quarks together through the exchange of particles called gluons. Quarks are particles that combine to form other subatomic particles such as protons and neutrons.

SEE ALSO Electron (1897), Photoelectric Effect (1905), Standard Model (1961), Quarks (1964), Theory of Everything (1984).

Modified Feynman diagram depicting the annihilation of an electron and a positron and creating a photon that decays into a new electron-positron pair.



+
+
γ
−
−

1948

Randomized Controlled Trials • *Clifford A. Pickover*

Austin Bradford Hill (1897–1991)

The design of tests for determining the efficacy of a medical treatment can be surprisingly difficult for many reasons. For example, physicians and test subjects may view results in a biased and nonobjective fashion. Treatment effects may be subtle, and patients may respond favorably simply due to the placebo effect, in which a patient thinks her condition is improving after taking a fake "treatment" (such as an inert sugar pill) that she *believes* should be effective.

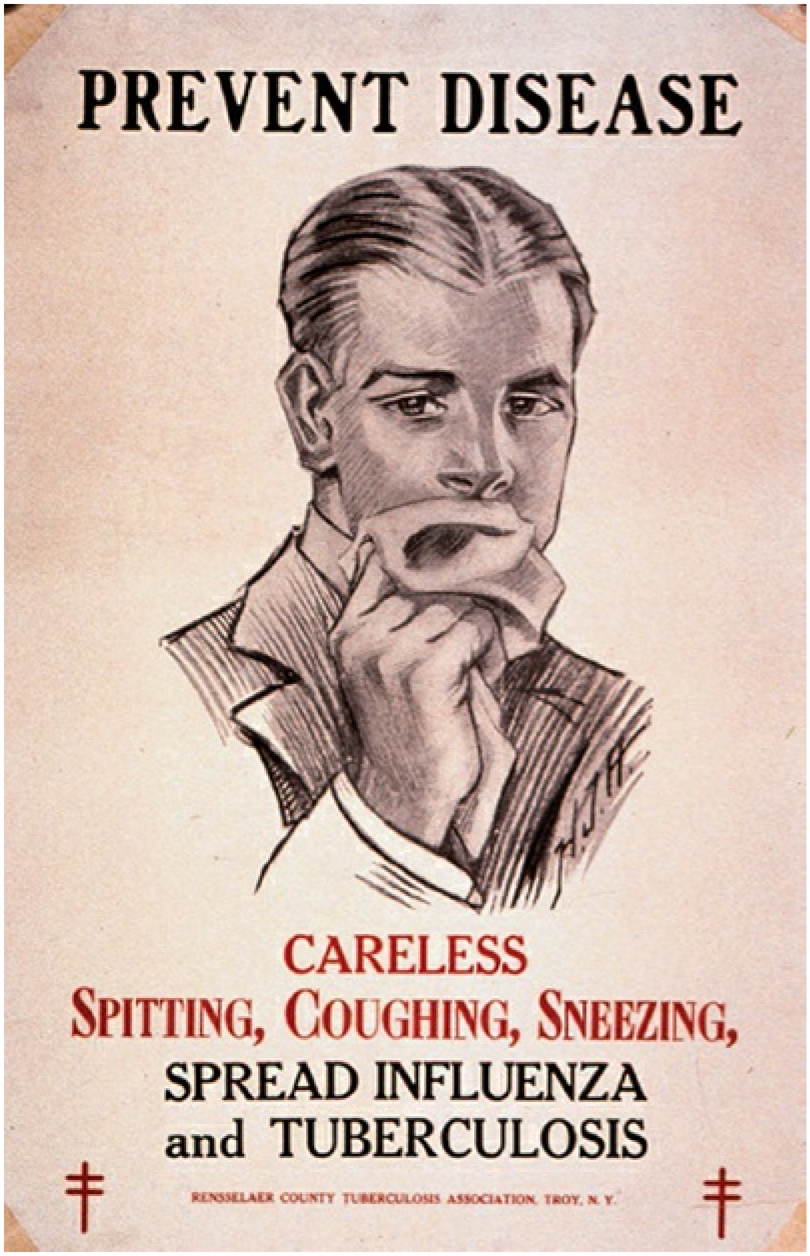
Today, one of the most reliable approaches for testing possible medical treatments is the randomized controlled trial (RCT). The nature of a treatment should be chosen at random, so that each patient has the same chance of getting each of the treatments under study. For example, each participant in the trial may randomly be assigned to one of two groups, with one group scheduled to receive medicine X and the other scheduled to receive medicine Y. RCTs may be double-blind, which implies that neither the primary researchers nor the patients know which patients are in the treated group (receiving a new drug) or the control group (receiving a standard treatment). For reasons of ethics, RCTs are usually performed when the researchers and physicians are genuinely uncertain about the preferred treatment.

The most famous early clinical study involving RCT is English statistician Bradford Hill's "Streptomycin Treatment of Pulmonary Tuberculosis," published in 1948 in the *British Medical Journal*. In this study, patients randomly received a sealed envelope containing a card marked S for streptomycin (an antibiotic) and bed rest, or C for control (bed rest only). Streptomycin was clearly shown to be effective.

Clinical epidemiologist Murray Enkin writes that this trial is “rightly regarded as a landmark that ushered in a new era of medicine. [Hundreds of thousands] of such trials have become the underlying basis for what is currently called ‘evidence-based medicine.’ The [RCT] concept has rightly been hailed as a paradigm shift in our approach to clinical decision making.”

SEE ALSO Aristotle’s *Organon* (c. 350 BCE), Scientific Method (1620), Placebo Effect (1955).

Public health campaign poster, trying to halt the spread of tuberculosis. In 1948, Bradford Hill published a study using RCTs to demonstrate the effectiveness of streptomycin to treat tuberculosis.


PREVENT DISEASE
CARELESS
SPITTING, COUGHING, SNEEZING,
SPREAD INFLUENZA
and TUBERCULOSIS
RENSSELAER COUNTY TUBERCULOSIS ASSOCIATION, TROY, N. Y.

1949

Radiocarbon Dating • *Clifford A. Pickover*

Willard Frank Libby (1908–1980)

“If you were interested in finding out the age of things, the University of Chicago in the 1940s was the place to be,” writes author Bill Bryson. “Willard Libby was in the process of inventing radiocarbon dating, allowing scientists to get an accurate reading of the age of bones and other organic remains, something they had never been able to do before. . . .”

Radiocarbon dating involves the measuring of the abundance of the radioactive element carbon-14 (^{14}C) in a carbon-containing sample. The method relies on the fact that ^{14}C is created in the atmosphere when cosmic rays strike nitrogen atoms. The ^{14}C is then incorporated into plants, which animals subsequently eat. While an animal is alive, the abundance of ^{14}C in its body roughly matches the atmospheric abundance. ^{14}C continually decays at a known exponential rate, converting to nitrogen-14, and once the animal dies and no longer replenishes its ^{14}C supply from the environment, the animal’s remains slowly lose ^{14}C. By detecting the amount of ^{14}C in a sample, scientists can estimate its age if the sample is not older than 60,000 years. Older samples generally contain too little of ^{14}C to measure accurately. ^{14}C has a half-life of about 5,730 years due to radioactive decay. This means that every 5,730 years, the amount of ^{14}C in a sample has dropped by half. Because the amount of atmospheric ^{14}C undergoes slight variations through time, small calibrations are made to improve the accuracy of the dating. Also, atmospheric ^{14}C increased during the 1950s due to atomic bomb tests. Accelerator mass spectrometry can be used to detect ^{14}C abundances in milligram samples.

Before radiocarbon dating, it was very difficult to obtain reliable dates before the First Dynasty in Egypt, around 3000 BCE. This was quite frustrating for archeologists who were feverish to know, for example, when Cro-Magnon people painted the caves of Lascaux in France or when the last Ice Age finally ended.

SEE ALSO Olmec Compass (c. 1000 BCE) Radioactivity (1896), Atomic Clocks (1955).

Because carbon is very common, numerous kinds of materials are potentially useable for radiocarbon investigations, including ancient skeletons found during archeological digs, charcoal, leather, wood, pollen, antlers, and much more.

1949

Time Travel • *Clifford A. Pickover*

Albert Einstein (1879–1955), **Kurt Gödel** (1906–1978), **Kip Stephen Thorne** (b. 1940)

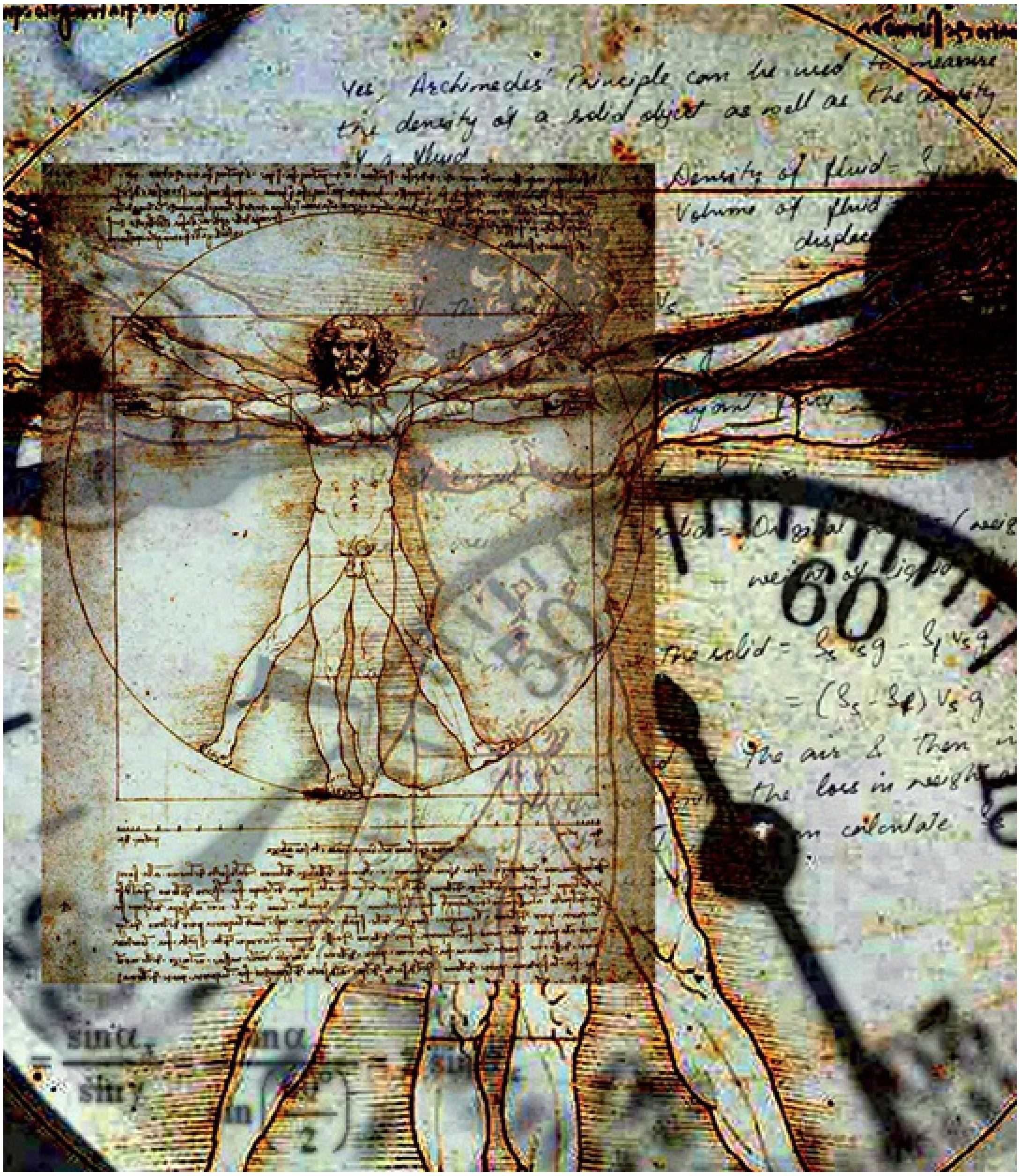
What is time? Is time travel possible? For centuries, these questions have intrigued philosophers and scientists. Today, we know for certain that time travel is possible. For example, scientists have demonstrated that objects traveling at high speeds age more slowly than a stationary object sitting in a laboratory frame of reference. If you could travel on a near light-speed rocket into outer space and return, you could travel thousands of years into the Earth's future. Scientists have verified this time slowing or "dilation" effect in a number of ways. For example, in the 1970s, scientists used atomic clocks on airplanes to show that these clocks had a slight slowing of time with respect to clocks on the Earth. Time is also significantly slowed near regions of very large masses.

Although seemingly more difficult, numerous ways exist in which time machines for travel to the past can theoretically be built that do not seem to violate any known laws of physics. Most of these methods rely on high gravities or on wormholes (hypothetical "shortcuts" through space and time). To Isaac Newton, time was like a river flowing straight. Nothing could deflect the river. Einstein showed that the river could curve, although it could never circle back on itself, which would be a metaphor for backwards time travel. In 1949, mathematician Kurt Gödel went even further and showed that the river could circle back on itself. In particular, he found a disturbing solution to Einstein's equations that allows backward time travel in a universe that rotated. For the first time in history, backward time travel had been given a mathematical foundation!

Throughout history, physicists have found that if phenomena are not expressly forbidden, they are often eventually found to occur. Today, designs for time travel machines are proliferating in top science labs and include such wild concepts as Thorne wormhole time machines, Gott loops that involve cosmic strings, Gott shells, Tipler and van Stockum cylinders, and Kerr rings. In the next few hundred years, perhaps our heirs will explore space and time to degrees we cannot currently fathom.

SEE ALSO Special Theory of Relativity (1905), General Theory of Relativity (1915), Atomic Clocks (1955).

If time is like space, might the past, in some sense, still exist "back there" as surely as your home still exists even after you have left it? If you could travel back in time, which genius of the past would you visit?


Yes, Archimedes' Principle can be used to measure
the density of a solid object as well as the density
Density of fluid
Volume of fluid
60

1950

Chess Computer • *Marshall Brain*

Alan Turing (1912–1954), **Claude Elwood Shannon** (1916–2001)

In 1950, American mathematician Claude Elwood Shannon wrote a paper about how to program a computer to play chess. In 1951, British mathematician and computer scientist Alan Turing was the first to produce a program that could complete a full game. Since then, software engineers have improved the software and computer hardware engineers have improved the hardware. In 1997, a custom computer called Deep Blue, developed by IBM, beat the best human player for the first time. Since then, humans have not had a chance because computer chess hardware and software keeps improving year after year.

How do engineers create a computer that can play chess? They do it by employing machine intelligence, which in the case of chess is very different from human intelligence. It is a brute force way to solve the chess problem.

Think of a board with a set of chess pieces on it. Engineers create a way to "score" that arrangement of pieces. The score might include the number of pieces on each side, the positions of the pieces, whether the king is well protected or not, etc. Now imagine a very simple chess program. You are playing black, the computer is playing white, and you have just made a move. The program could try moving every white piece to every possible valid position, scoring the board on each move. Then it would pick the move with the best score. This program would not play very well, but it could play chess.

What if the computer went a step further? It moves every white piece to every possible position. Then on each possible white move, it tries every black move, and scores all of those boards. The number of possible moves that the computer has to score has grown significantly, but now the computer can play better.

What if the computer looks multiple levels ahead? The number of boards the computer has to score explode with each new level. The computer gets better. When Deep Blue won in 1996, it was able to score 200 million boards per second. It had memorized all common openings and gambits. It could prune out vast numbers of moves by realizing certain paths were unproductive. In 2017, the program AphaZero beat world-champion chess-playing computer programs, having taught itself how to play in less than a day!

SEE ALSO Slide Rule (1621), Babbage Mechanical Computer (1822), ENIAC (1946), Transistor (1947).

Pictured: IBM’s supercomputer, Deep Blue.


03

1950

Fermi Paradox • *Clifford A. Pickover*

Enrico Fermi (1901–1954), **Frank Drake** (b. 1930)

During our Renaissance, rediscovered ancient texts and new knowledge flooded medieval Europe with the light of intellectual transformation, wonder, creativity, exploration, and experimentation. Imagine the consequences of making contact with an alien race. Another, far more profound Renaissance would be fueled by the wealth of alien scientific, technical, and sociological information. Given that our universe is both ancient and vast—there are an estimated 250 billion stars in our Milky Way galaxy alone—the physicist Enrico Fermi asked in 1950, “Why have we not yet been contacted by an extraterrestrial civilization?” Of course, many answers are possible. Advanced alien life could exist, but we are unaware of their presence. Alternatively, intelligent aliens may be so rare in the universe that we may never make contact with them. The Fermi Paradox, as it is known today, has given rise to scholarly works attempting to address the question in fields ranging from physics and astronomy to biology.

In 1960, astronomer Frank Drake suggested a formula to estimate the number of extraterrestrial civilizations in our galaxy with whom we might come into contact:

$$N = R^* \times f_p \times n_\mathrm{e} \times f_\ell \times f_\mathrm{i} \times f_\mathrm{c} \times L$$

Here, N is the number of alien civilizations in the Milky Way with which communication might be possible; for example, alien technologies may produce detectable radio waves. R^* is the average rate of star formation per year in our galaxy. f_p is the fraction of those stars that have planets (hundreds of extra solar planets have been detected). n_e is the average number of "Earth-like" planets that can potentially support life per star that has planets. f_ℓ is the fraction of these n_e planets that actually yield life forms. f_i is the fraction of f_ℓ that actually produce intelligent life. The variable f_c represents the fraction of civilizations that develop a technology that releases detectable signs of their existence into outer space. L is the length of time such civilizations release signals into space that we can detect. Because many of the parameters are very difficult to determine, the equation serves more to focus attention on the intricacies of the paradox than to resolve it.

SEE ALSO Time Travel (1949), Miller-Urey Experiment (1952), First Humans in Space (1961).

Given that our universe is both ancient and vast, the physicist Enrico Fermi asked in 1950, "Why have we not yet been contacted by an extraterrestrial civilization?"

1951

HeLa Cells • *Clifford A. Pickover*

George Otto Gey (1899–1970), **Henrietta Lacks** (1920–1951)

Medical researchers use human cells grown in the laboratory to study cell functions and to develop treatments for diseases. Such cells can be frozen and shared among different researchers. However, most cell lines divide only a limited number of times and then die. A breakthrough occurred in 1951, when American biologist George Gey cultured cells removed from a cancerous tumor of the cervix and created the first immortal human cells. These HeLa cells, named after the unwitting donor, Henrietta Lacks, continue to multiply to this day. Gey freely gave the cells to any scientists who requested them, and more than 60,000 scientific articles and 11,000 patents have since been published relating to research performed on the cells.

Author Rebecca Skloot writes, “If you could pile all HeLa cells ever grown onto a scale, they’d weigh more than 50 million metric tons—as much as a hundred Empire State Buildings. HeLa cells were vital for developing the polio vaccine; uncovered secrets of **cancer**, viruses, and the effects of the atom bomb; helped lead to important advances like in vitro fertilization, cloning, and gene mapping; and have been bought and sold by the billions.”

HeLa cells contain an active **telomerase** enzyme that continually repairs the ends of chromosomes that would normally become too damaged after multiple cell divisions to permit the cells to continue propagating. The genetic makeup of HeLa cells is far from ordinary, as they contain genes from human papillomavirus 18 and extra copies of several human chromosomes. Because the cells are so prolific and can even be spread on particles through the air, they have contaminated many other cell cultures in laboratories.

Lacks died at age 31 from the spread of her cancer, and her family did not learn of her “immortality” until decades later. The cells have since been launched into space to test the effects of low gravity and have been used in research topics ranging from AIDS to the testing of toxic substances.

SEE ALSO Causes of Cancer (1761), Cell Division (1855), Discovery of Viruses (1892), Chromosomal Theory of Inheritance (1902).

Scanning electron micrograph of HeLa cells dividing.

1952

Cellular Automata • *Clifford A. Pickover*

John von Neumann (1903–1957), **Stanisław Marcin Ulam** (1909–1984), **John Horton Conway** (b. 1937)

Cellular automata are a class of simple mathematical systems that can model a variety of physical processes with complex behaviors. Applications include the modeling of the spread of plant species, the propagation of animals such as barnacles, the oscillations of chemical reactions, and the spread of forest fires.

Some of the classic cellular automata consist of a grid of cells that can exist in two states, occupied or unoccupied. The occupancy of one cell is determined from a simple mathematical analysis of the occupancy of neighbor cells. Mathematicians define the rules, set up the game board, and let the game play itself out on a checkerboard world. Though the rules governing the creation of cellular automata are simple, the patterns they produce are very complicated and sometimes seem almost random, like a turbulent fluid flow or the output of a cryptographic system.

Early work in this area began with Stanislaw Ulam in the 1940s, when he modeled the growth of crystals using a simple lattice. Ulam suggested that mathematician John von Neumann use a similar approach to modeling self-replicating systems, such as robots that could build other robots, and around 1952, von Neumann created the first 2-D cellular automata, with 29 states per cell. Von Neumann proved mathematically that a particular pattern could make endless copies of itself within the given cellular universe.

The most famous two-state, two-dimensional cellular automaton is the Game of Life invented by John Conway, and popularized by Martin Gardner in *Scientific American*. Despite its simple rules, an amazing diversity of behaviors and forms are generated including gliders—that is, arrangements of cells that move themselves across their universe and can even interact to perform computations. In 2002, Stephen Wolfram published *A New Kind of Science*, which reinforced the idea that cellular automata can have significance in virtually all disciplines of science.

SEE ALSO Turing Machines (1936), Information Theory (1948), Chaos and the Butterfly Effect (1963), Fractals (1975).

Cone snail with cellular-automata patterns on its shell, resulting from that activation and inhibition of neighboring pigment cells. The pattern resembles the output of a one-dimensional cellular automaton, referred to as a Rule 30 automaton.

1952

Miller-Urey Experiment • *Derek B. Lowe*

Harold C. Urey (1893–1981), **Stanley Miller** (1930–2007)

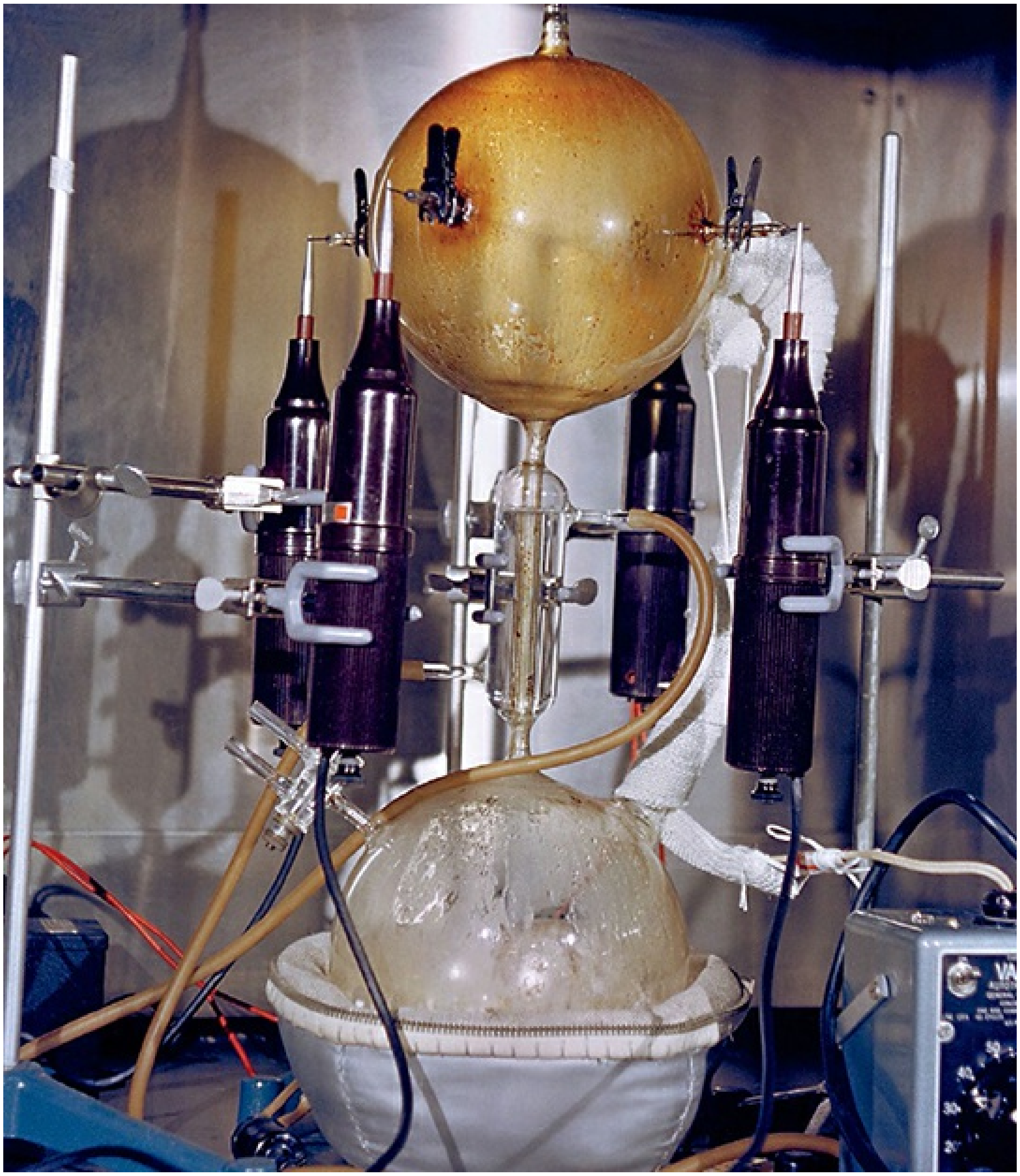
For thousands of years, humankind has been trying to understand the origin of life. Biochemistry had to start somewhere, and presumably was much simpler at the beginning. But what did that beginning look like, and how did it get going? Could it happen again on other planets? How similar, then, would it be to what we know? None of these questions have a good answer yet.

A major step forward was taken in 1952 by American chemists Stanley Miller and Harold C. Urey. The idea was to take a believable "prebiotic" atmosphere and subject it to heat and the equivalent of lightning to see what compounds might form. They sealed an apparatus with water, methane, ammonia, and hydrogen; heated the water; fired electrical sparks across the vapor; and then cooled the system again to send the condensate back into the water layer. The process was set to cycle repeatedly, and it began to make colored compounds during the first day. After two weeks, over 10 percent of the methane had been turned into more complex compounds, and analysis of the mixture was startling. At least eleven of the twenty key amino acids were present, along with many simple carbohydrates and a variety of other molecules. Modern re-analysis of the sample has shown that all of the major amino acids were produced, some of them originally below the limits of detection.

Many similar experiments have been run since, using all sorts of different possible early atmospheres and conditions. Almost all of them produce rich brews of simple organic compounds, including many of what we would now call the building blocks of life. These arise through the formation of reactive molecules like hydrogen cyanide and formaldehyde from the original gases, which can go on to produce complex structures. The mixture of compounds in samples like the Murchison meteorite can be quite similar to those produced by these experiments, and spectroscopic studies have found many of these compounds around other stars as well as in comets and interstellar nebulae. The universe appears to be swimming in small biomolecules.

SEE ALSO Refuting Spontaneous Generation (1668), Fermi Paradox (1950), Darwin's Theory of Natural Section (1859).

A re-creation at NASA of the Miller-Urey experiment. Note the dark mixture already forming in the chamber. Such brews of organic molecules seem to have many opportunities to form in the universe.



1953

DNA Structure • *Clifford A. Pickover*

Maurice Hugh Frederick Wilkins (1916–2004), **Francis Harry Compton Crick** (1916–2004), **Rosalind Elsie Franklin** (1920–1958), **James Dewey Watson** (b. 1928)

The British journalist Matt Ridley writes, “The double helix [structure of DNA] has been a shockingly fecund source of new understanding—about our bodies and minds, our past and future, our crimes and illnesses.” The DNA (deoxyribonucleic acid) molecule may be thought of as a “blueprint” that contains hereditary information. It also controls protein production and the complex development of cells starting from a fertilized egg. Just as an error in an architectural blueprint for a building might lead to home collapses or leaks, errors in the DNA, such as changes in the sequence caused by mutagens, might lead to disease. Thus, an understanding of the messages in the DNA can lead to cures for disease, including the development of new drugs.

At a molecular level, DNA resembles a twisted ladder in which the different rungs of the ladder (referred to as bases) represent a code for protein production. DNA is organized into structures called chromosomes, and the human genome has approximately three billion DNA base pairs in the 23 chromosomes of each sperm cell or egg. Generally speaking, a gene is a sequence of DNA that contains a “chunk” of information that, for example, specifies a particular protein.

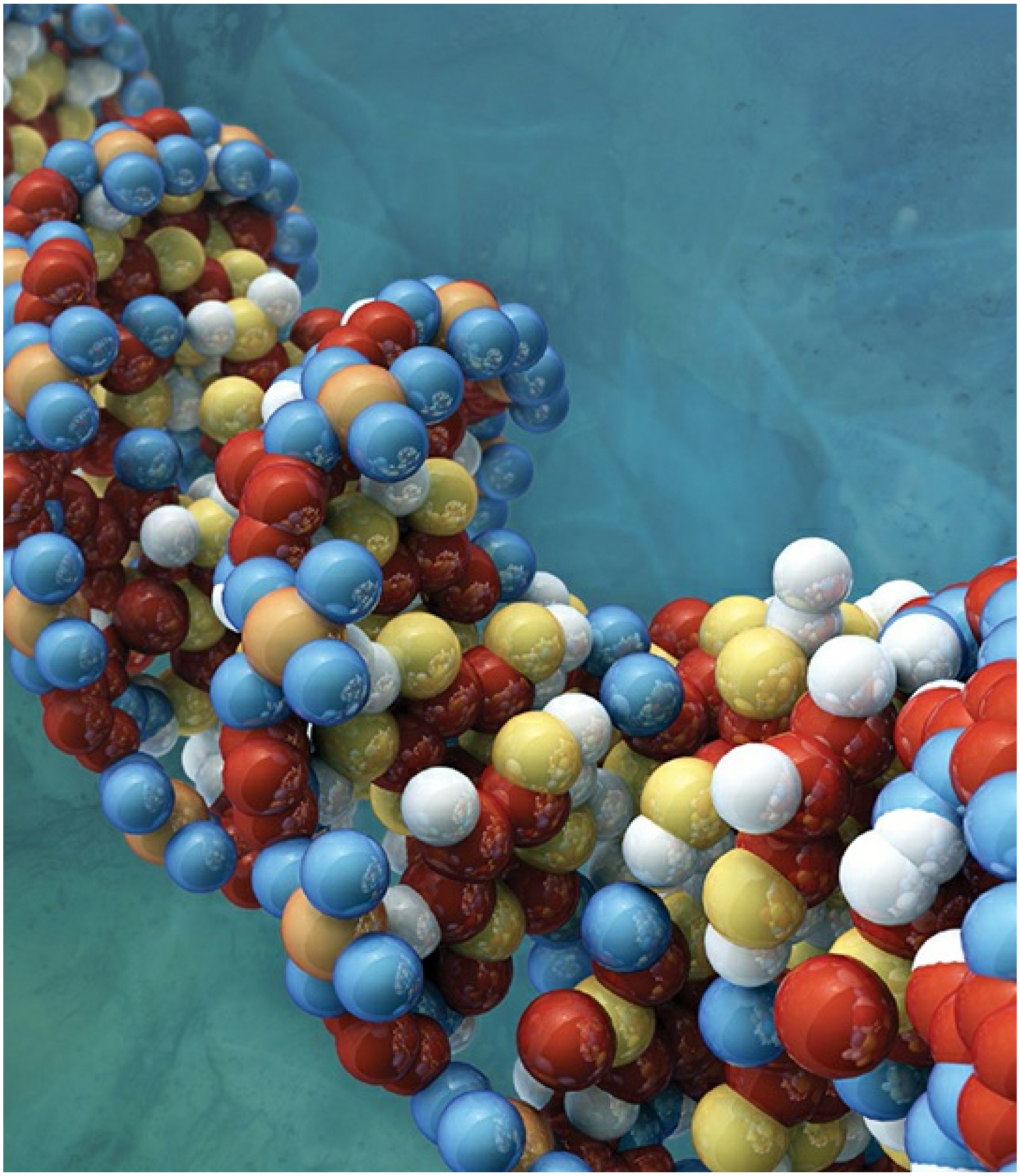
In 1953, molecular biologists James Watson and Francis Crick discovered the double helical structure of DNA using molecular-modeling methods, along with X-ray and other data from scientists such as Maurice Wilkins and

Rosalind Franklin. Today, with recombinant DNA technology, genetically modified organisms can be created by inserting new DNA sequences that force the organism to create desirable products, such as insulin to be used by humans. Forensic detectives can study DNA left at crime scenes to help identify potential criminals.

In December 1961, the *New York Times* reported on breakthroughs in understanding of the genetic code in DNA by explaining that "the science of biology has reached a new frontier," leading to "a revolution far greater in its potential significance than the atomic or hydrogen bomb."

SEE ALSO Mendel's Genetics (1865), Chromosomal Theory of Inheritance (1902), Epigenetics (1983), Polymerase Chain Reaction (1983), Human Genome Project (2003), Gene Therapy (2016).

Molecular model of a portion of a DNA strand.



1955

Atomic Clocks • *Clifford A. Pickover*

Louis Essen (1908–1997)

Clocks have become more accurate through the centuries. Early mechanical clocks, such as the fourteenth-century Dover Castle clock, varied by several minutes each day. When pendulum clocks came into general use in the 1600s, clocks became accurate enough to record minutes as well as hours. In the 1900s, vibrating quartz crystals were accurate to fractions of a second per day. In the 1980s, cesium atom clocks lost less than a second in 3,000 years, and, in 2009, an atomic clock known as NIST-F1—a cesium fountain atomic clock—was accurate to a second in 60 million years!

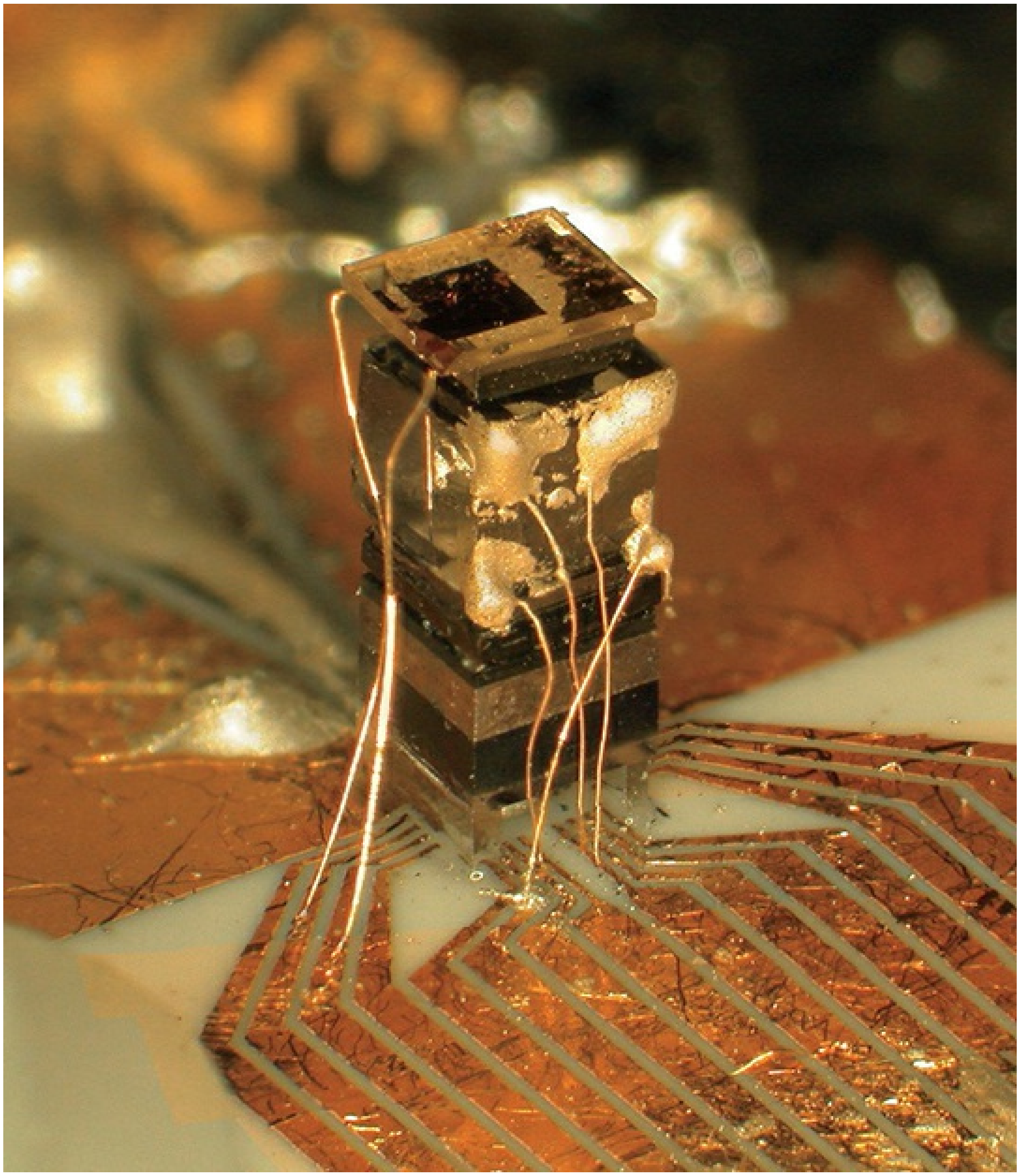
Atomic clocks are accurate because they involve the counting of periodic events involving two different energy states of an atom. Identical atoms of the same isotope (atoms having the same number of nucleons) are the same everywhere; thus, clocks can be built and run independently to measure the same time intervals between events. One common type of atomic clock is the cesium clock, in which a microwave frequency is found that causes the atoms to make a transition from one energy state to another. The cesium atoms begin to fluoresce at a natural resonance frequency of the cesium atom (9,192,631,770 Hz, or cycles per second), which is the frequency used to define the second. Measurements from many cesium clocks throughout the world are combined and averaged to define an international time scale.

One important use of atomic clocks is exemplified by the GPS (global positioning system). This satellite-based system enables users to determine their positions on the ground. To ensure accuracy, the satellites must send out accurately timed radio pulses, which receiving devices need to determine their positions.

English physicist Louis Essen created the first accurate atomic clock in 1955, based on energy transitions of the cesium atom. Clocks based on other atoms and methods are continually being researched in labs worldwide in order to increase accuracy and decrease cost.

SEE ALSO Sundial (c. 3000 BCE) Time Travel (1949), Radiocarbon Dating (1949).

In 2004, scientists at the National Institute of Standards and Technology (NIST) demonstrated a tiny atomic clock, the inner workings of which were about the size of a grain of rice. The clock included a laser and a cell containing a vapor of cesium atoms.



1955

Birth-Control Pill • *Clifford A. Pickover*

Margaret Higgins Sanger Slee (1879–1966), **Pope Paul VI** (**Giovanni Montini;** 1897–1978), **Gregory Pincus** (1903–1967), **Frank Benjamin Colton** (1923–2003), **Carl Djerassi** (1923–2015)

Oral contraceptives, or birth-control pills, were among the most socially significant medical advances of the twentieth century. Supplied with an easy and effective means to prevent pregnancies, more women graduated from college and entered the work force. In the 1930s, researchers had determined that high concentrations of the hormone progesterone, which is normally present during pregnancy, also tricks a nonpregnant body into behaving as if it were pregnant and thus prevent the monthly release of an egg. In the early 1950s, American chemists Carl Djerassi and Frank Colton, working independently, discovered ways to manufacture chemical compounds that mimicked natural progesterone. American biologist Gregory Pincus confirmed that shots of progesterone prevent egg release from the ovary of mammals.

Margaret Sanger, a famous advocate for birth control, helped Pincus obtain the necessary funding to develop a hormonal birth-control pill for humans. Pincus selected Colton's formula, and in 1955 he and colleagues announced clinical-trial results demonstrating the efficacy of the pill. In addition to inhibiting ovulation, contraception is enhanced by changes in the cervical mucus that inhibit **sperm** entrance to the uterus, and by changes in the lining of the uterus that inhibit egg implantation. U.S. regulators approved the pill for contraception in 1960, and the Searle drug company named it Enovid.

The original formulation, which also contained the hormone estrogen, had some undesirable side effects; however, modern formulations contain much reduced doses of hormones and have been shown to decrease ovarian, endometrial, and colon cancers. Generally speaking, women smokers who take the pill have an increased risk of heart attacks or strokes. Today, different hormonal formulations are available (including pills only with progestin, a type of progesterone) that supply hormone doses that are constant or that change from one week to the next.

In 1968, Pope Paul VI condemned artificial birth control, including the pill. Although adoption of the pill was rapid in the United States, distribution of contraceptives to unmarried women was not legal in Connecticut until 1972!

SEE ALSO Discovery of Sperm (1678), Cell Division (1855), Chromosomal Theory of Inheritance (1902).

A psychedelic portrait of a "post-pill paradise" in a new era for women. In the 1960s, many women achieved greater personal control over contraception, which contributed to the sexual revolution.


PEACE
LOVE
MUSIC

1955

Placebo Effect • *Clifford A. Pickover*

Henry Knowles Beecher (1904–1976)

Medical experts Arthur and Elaine Shapiro write, “The panorama of treatment since antiquity provides ample support for the conviction that, until recently, the history of medical treatment is essentially the history of the placebo effect. . . . For example, the first three editions of the *London Pharmacopoeia* published in the seventeenth century included such useless drugs as usnea (moss from the skull of victims of violent death) and Vigo’s plaster ([including] viper’s flesh, live frogs, and worms).”

Today, the term *placebo* often refers to a fake “drug” (such as a sugar pill) or a sham surgery (such as cutting the skin but going no deeper to treat a condition) that nevertheless produces a perceived or actual improvement in those patients who believe the medical intervention will turn out to be effective. The placebo effect suggests the importance of patient expectations and the role of the brain in physical health, particularly for subjective outcomes such as levels of pain.

In 1955, American physician Henry Beecher documented the famous case of soldiers in World War II who experienced significant pain relief when given injections of saline solutions when the morphine supplies were not available. One mechanism of the placebo effect appears to involve endogenous opioids—natural painkillers produced by the brain—as well as the activity of the neurotransmitter dopamine.

In one study, mice given a compound that suppresses the immune system along with a sweet-tasting chemical became conditioned over time, so that immune suppression occurred when given only the sweetener. Thus, conditioning may play a role in human placebos. A placebo administered to people as a stimulant can increase blood pressure, and alcohol placebos can cause intoxication. Color and size of pills often make a significant difference in perceived effectiveness. The placebo effect also tends to work to varying degrees depending on the society and country tested. A nocebo response refers to a negative response to a placebo, such as the feeling of pain when the patient believes that the inert drug may have unpleasant side effects.

SEE ALSO Scientific Method (1620), *The Principles of Psychology* (1890), Psychoanalysis (1899), Randomized Controlled Trials (1948), Classical Conditioning (1903), Theory of Mind (1978).

Because a person's expectations influence the placebo effect, the pill color, size, and shape all affect the placebo response. Red pills work better as stimulants, while "cool"-colored pills work better as depressants. Capsules are often perceived to be particularly effective.

1955

Ribosomes • *Michael C. Gerald with Gloria E. Gerald*

Albert Claude (1898–1983), **George Palade** (1912–2008)

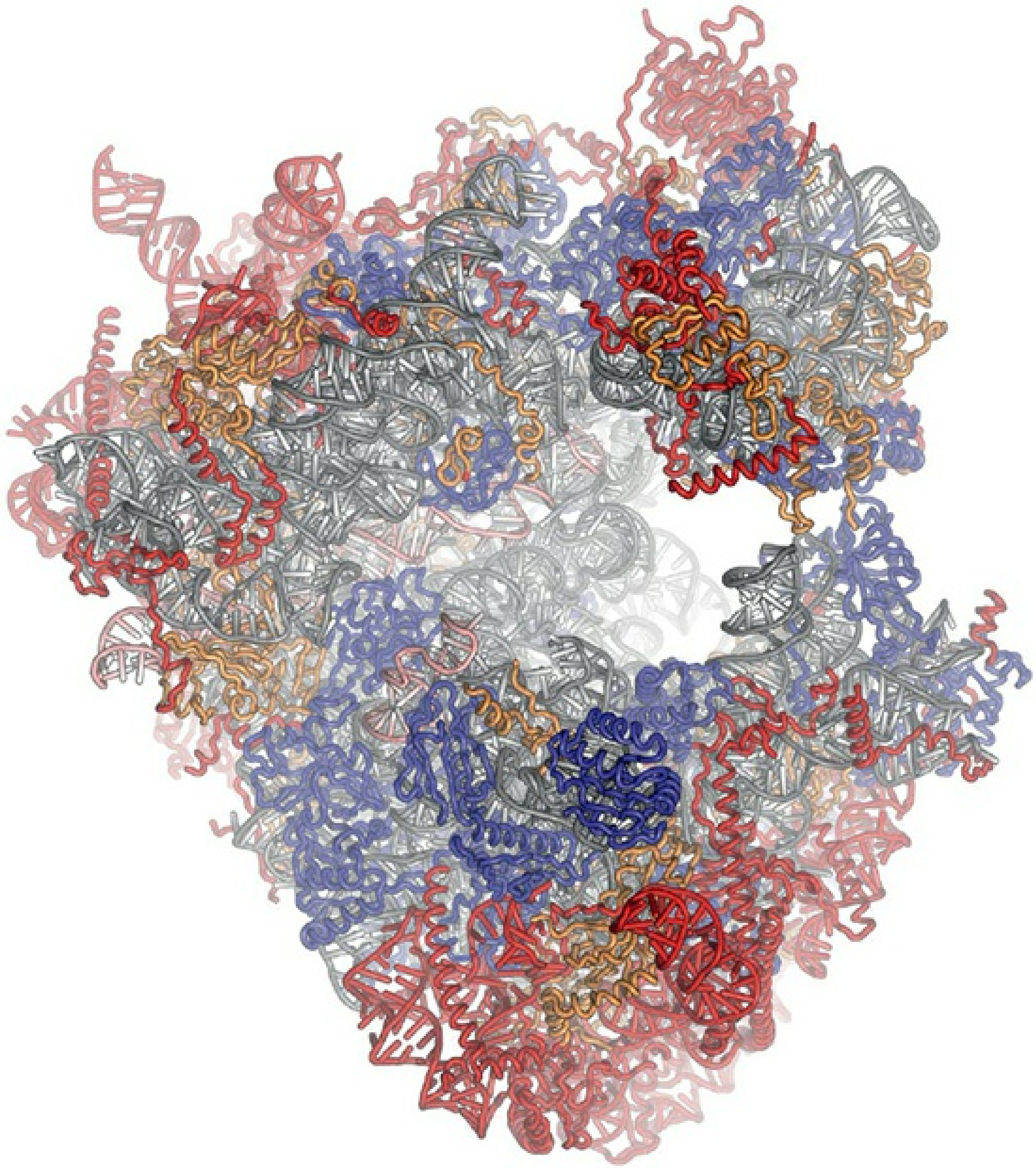
The combination of cell fractionation and electron microscopy opened a new frontier in biology, making possible the visualization of the cell's interior contents and determining their biological functions. In 1930, the Belgian biologist Albert Claude, at Rockefeller University, devised the process of cell fractionation, in which a cell is ground up to release its contents and centrifuged at different speeds to separate the contents according to weight. Claude's cell fractionation process was refined in 1955 by his student George Palade, a Romanian-born American, who used the electron microscope to study these cell fractions. Palade was first to identify and describe "small granules," which were given the name *ribosome* in 1958, and found to be the site of protein synthesis within the cell. Claude and Palade (the latter often called the father of modern cell biology and the most influential cell biologist ever) were co-recipients of the 1974 Nobel Prize.

THE PROTEIN FACTORY. All living organisms have ribosomes within each of their cells that are directed by the genetic code to function as factories, carrying out the synthesis of proteins. Cells having high rates of protein synthesis, such as the pancreas, have millions of ribosomes. DNA carries instructions to messenger RNA (mRNA) for building specific proteins. Transfer RNA (tRNA) then brings the amino acids to the ribosome where they are sequentially added to a growing protein chain.

Ribosomes found in eukaryotic cells (animals, plants, fungi) and prokaryotic (bacterial) cells have a similar structure and function. In the former, they are attached to rough-endoplasmic reticular membranes and, in the latter, suspended in the cytosol, the fluid component of cytoplasm. That ribosomes are found across all kingdoms of life suggests that the ribosome evolved early in the evolutionary process. Palade determined that ribosomes are made up of large and small subunits and that there are subtle differences in density (mass per unit volume) between the ribosomes in prokaryotic and eukaryotic cells. This is of practical significance in the treatment of bacterial infections. Certain antibiotics, such as erythromycin and the tetracyclines, selectively inhibit the protein synthesis in bacteria without having such effects in the patient's cells.

SEE ALSO Cell Nucleus (1831), Enzymes (1878), Penicillin (1928), DNA Structure (1953), Cracking the Genetic Code for Protein Biosynthesis (1961).

The primary function of ribosomes is the manufacture of proteins. The image depicts a model of a eukaryotic ribosome, which differs in structure from a prokaryotic ribosome.



1956

Parallel Universes • *Clifford A. Pickover*

Hugh Everett III (1930–1982), **Max Tegmark** (b. 1967)

A number of prominent physicists now suggest that universes exist that are parallel to ours and that might be visualized as layers in a cake, bubbles in a milkshake, or buds on an infinitely branching tree. In some theories of parallel universes, we might actually detect these universes by gravity leaks from one universe to an adjacent universe. For example, light from distant stars may be distorted by the gravity of invisible objects residing in parallel universes only millimeters away. The entire idea of multiple universes is not as far-fetched as it may sound. According to a poll of 72 leading physicists conducted by the American researcher David Raub and published in 1998, 58% of physicists (including Stephen Hawking) believe in some form of multiple universes theory.

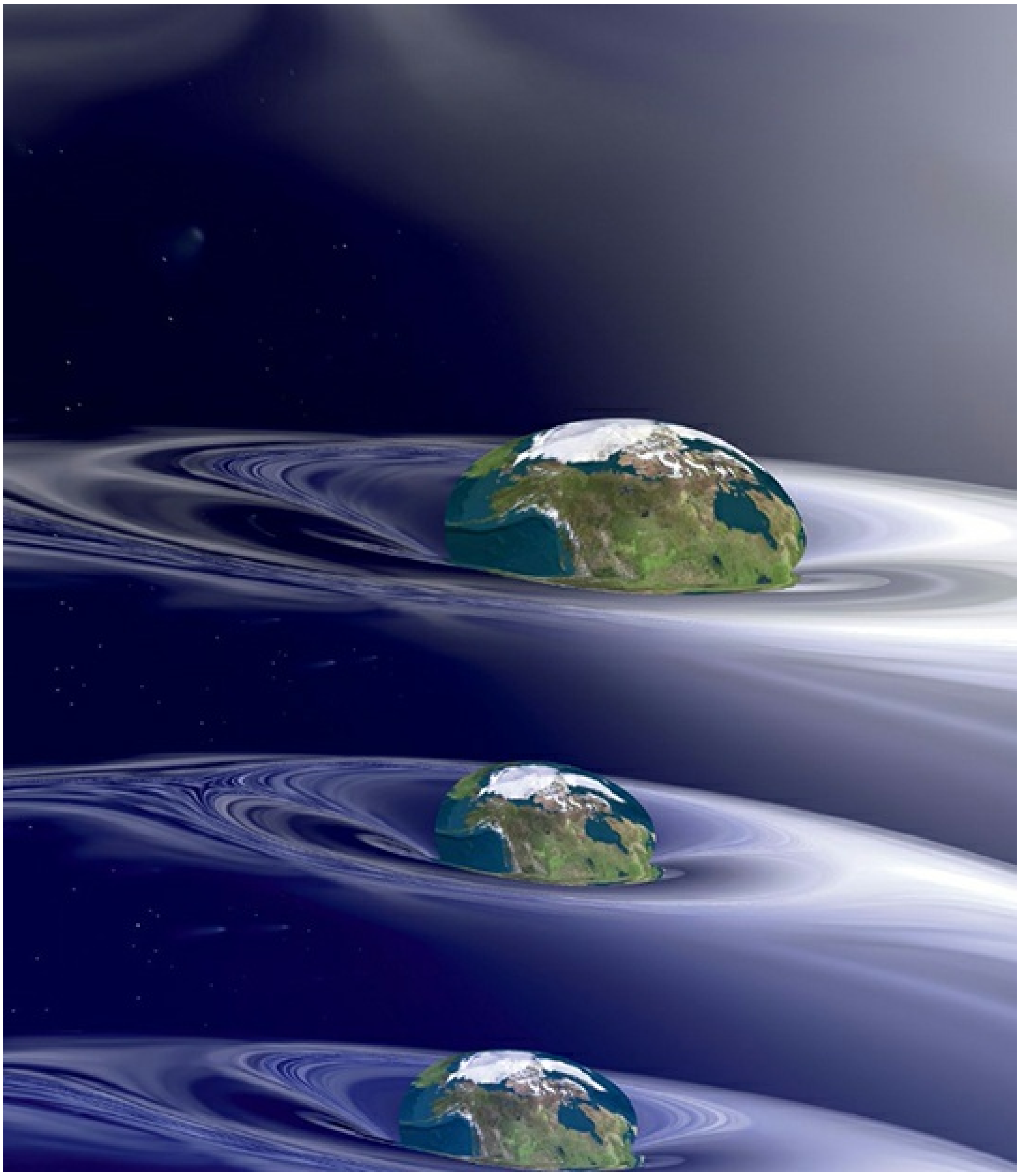
Many flavors of parallel-universe theory exist. For example, Hugh Everett III's 1956 doctoral thesis "The Theory of the Universal Wavefunction" outlines a theory in which the universe continually "branches" into countless parallel worlds. This theory is called the many-worlds interpretation of quantum mechanics and posits that whenever the universe ("world") is confronted by a choice of paths at the quantum level, it actually follows the various possibilities. If the theory is true, then all kinds of strange worlds may "exist" in some sense. In a number of worlds, Hitler won World War II. Sometimes, the term "multiverse" is used to suggest the idea that the universe that we can readily observe is only part of the reality that comprises the multiverse, the set of possible universes.

If our universe is *infinite*, then identical copies of our visible universe may exist, with an exact copy of our Earth and of you. According to physicist Max

Tegmark, on average, the nearest of these identical copies of our visible universe is about 10 to the 10^{100} meters away. Not only are there infinite copies of you, there are infinite copies of variants of you. Chaotic cosmic inflation theory also suggests the creation of different universes—with perhaps countless copies of you existing but altered in fantastically beautiful and ugly ways.

SEE ALSO Wave Nature of Light (1801), Schrödinger's Cat (1935), Cosmic Inflation (1980), Quantum Computers (1981).

Some interpretations of quantum mechanics posit that whenever the universe is confronted by a choice of paths at the quantum level, it actually follows the various possibilities. Multiverse implies that our observable universe is part of a reality that includes other universes.



1957

Antidepressant Medications • *Wade E. Pickren*

Roland Kuhn (1912–2005)

In 1952, a drug under development for use with tuberculosis patients, iproniazid, was found to be effective in treating depression. Approved for use in 1958, it was withdrawn three years later when it was found to cause serious liver damage. In 1955, imipramine was being considered as a treatment for people suffering from schizophrenia at a mental hospital in Switzerland, but the results were not positive. Psychiatrist Roland Kuhn decided to try the drug on forty depressed patients, and the results were all positive. Patients became livelier, their voices were stronger, they were able to effectively communicate, and hypochondriacal complaints all but disappeared. He published his results in 1957.

Imipramine moved to the market under the brand name Tofranil. It was the first of what soon became a family of drugs labeled tricyclics (so named because of their three-ring chemical structure). Tricyclics work by inhibiting the reuptake of the neurotransmitters norepinephrine and, to a lesser degree, serotonin, thus initially making more of them available for use in the brain. There can be unpleasant side effects, however, such as dry mouth, constipation, weight gain, and sexual dysfunction.

Another antidepressant that also works by inhibition was discovered shortly after imipramine. The class of drugs known as monoamine oxidase inhibitors (MAOI) prevents the action of an enzyme, monoamine oxidase, which breaks down such neurotransmitters as serotonin and norepinephrine. MAOI side effects are even more dangerous than those of the tricyclics, so they are seldom prescribed today.

In 1987, a second-generation antidepressant with the trade name Prozac was approved for use by the US Food and Drug Administration. Prozac and other drugs like it are selective serotonin reuptake inhibitors (SSRIs). Just as their name implies, they inhibit the reuptake of serotonin in the synapse. The response has been phenomenal: within three years of its release, Prozac was the number-one drug prescribed by psychiatrists, and by 1994 it was the number-two best-selling drug of any kind in the world. It does not have many of the side effects of other antidepressants. Indeed, it is used by millions of people who suffer from no mental disorder at all but who use the drug to enhance their personality, lose weight, or increase their attention spans.

SEE ALSO Morgagni's "Cries of Suffering Organs," Neuron Doctrine (1891), Cerebral Localization (1861), Psychoanalysis (1899), Cognitive Behavior Therapy (1963).

Many species of passionflower have been found to contain beta-carboline harmala alkaloids, which are MAO inhibitors with antidepressant properties.

1957

Space Satellite • *Marshall Brain*

Think about your typical satellite, for example a photographic satellite that takes pictures of the Earth. On the one hand it is not that complicated. It has a high-resolution digital camera attached to a telescope that acts as a lens. It has solar panels and batteries to provide electricity. It has a radio to communicate with Earth and an antenna. There's nothing really surprising. These are the same parts you would expect to find on any remote camera system—the camera itself, a power source, and a radio link.

So why does a satellite like this cost millions of dollars? It is largely because of the special considerations that go along with flying in space. Engineers have to keep the satellite functioning in an inaccessible, harsh environment. These challenges were first faced when Russian scientists launched the first space satellite, Sputnik 1, in 1957. Since then, satellites have gotten far more sophisticated.

Take for example the computer in a modern satellite. Engineers cannot use a normal computer in space. Everything must be radiation hardened at the time of manufacture to prevent cosmic rays, solar particles, and other forms of radiation from disrupting the circuits. The computer will then be triple redundant, with a voting system to detect if one of the three fails.

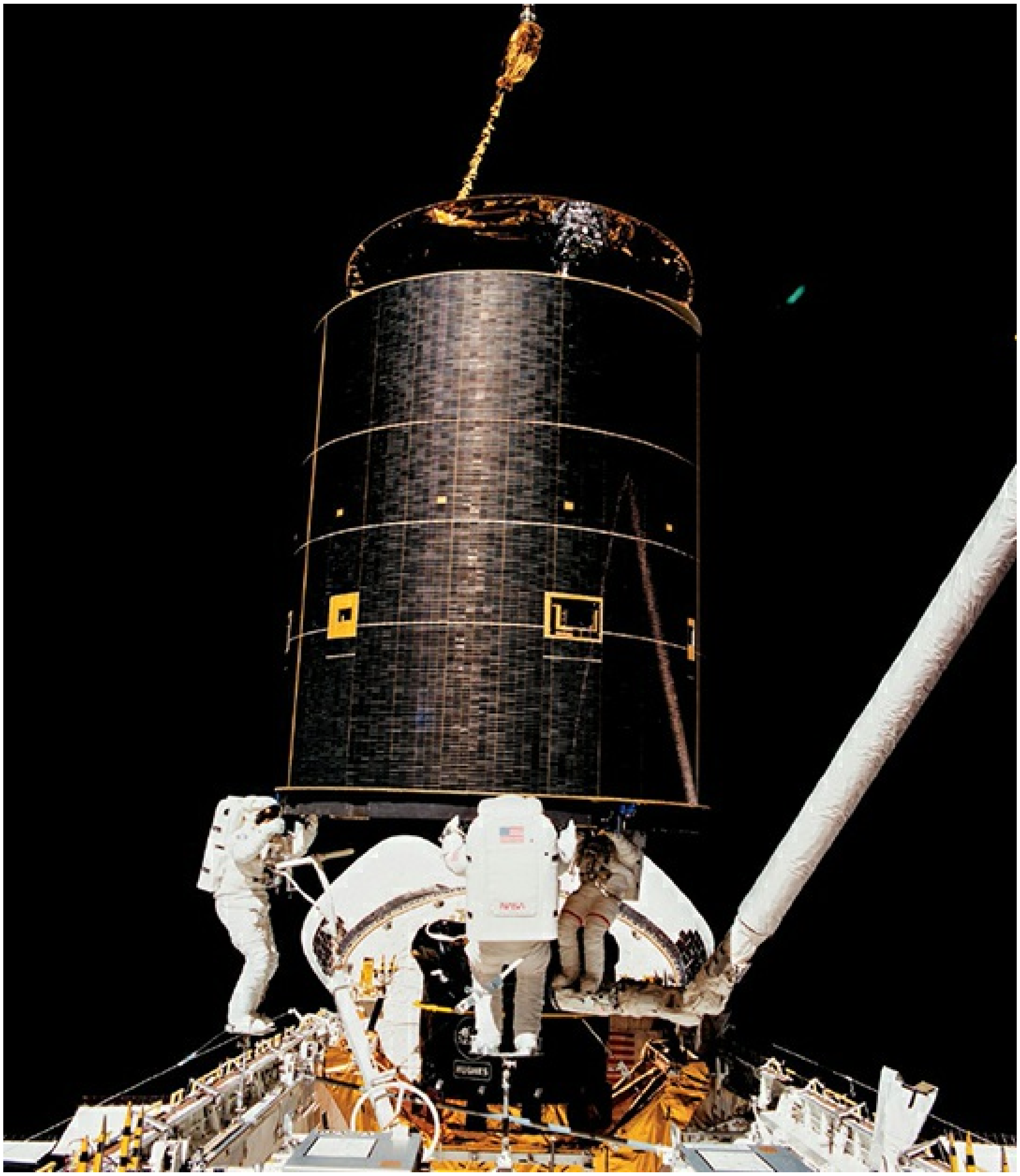
The satellite has to keep itself properly oriented at all times. It usually does this with a combination of sun trackers, star trackers, and reaction wheels. The reaction wheels can speed up or slow down in order to change the orientation of the satellite. There will also be thrusters and plenty of fuel (e.g., 300 pounds or 150 kg) to last a decade or more.

The solar cells are not typical. They are radiation-hardened, high-efficiency cells. And the batteries are not standard either. Engineers have created special nickel-hydrogen batteries that handle tens of thousands of charge/discharge cycles and can last more than a decade.

And then there is one final thing: a massive amount of reliability testing, certification, redundancy, etc., including assembly in a clean-room environment, testing in a hard vacuum, vibration tests, and so on. There is no way to repair the satellite if something goes wrong, and it has to work for many years in space. All of this work and all of these special components make any satellite an expensive proposition.

SEE ALSO First Humans in Space (1961), Hubble Telescope (1990), Global Positioning System (GPS) (1994).

Three crew members of mission STS-49 hold on to the 4.5-ton International Telecommunications Organization Satellite (INTELSAT) VI, 1992.



1958

Central Dogma of Molecular Biology •

Michael C. Gerald with Gloria E. Gerald

Francis Crick (1916–2004), **James D. Watson** (b. 1928), **Howard Temin** (1934–1994), **David Baltimore** (b. 1938)

In 1958, five years after Watson and Crick discovered the molecular structure of deoxyribonucleic acid (DNA)—the double helix—Crick proposed the central dogma of molecular biology, and this he popularized in a paper in *Nature* in 1970. In its basic terms, the central dogma states that genetic information flows in only one direction from DNA ("transcription") to RNA ("translation") to proteins.

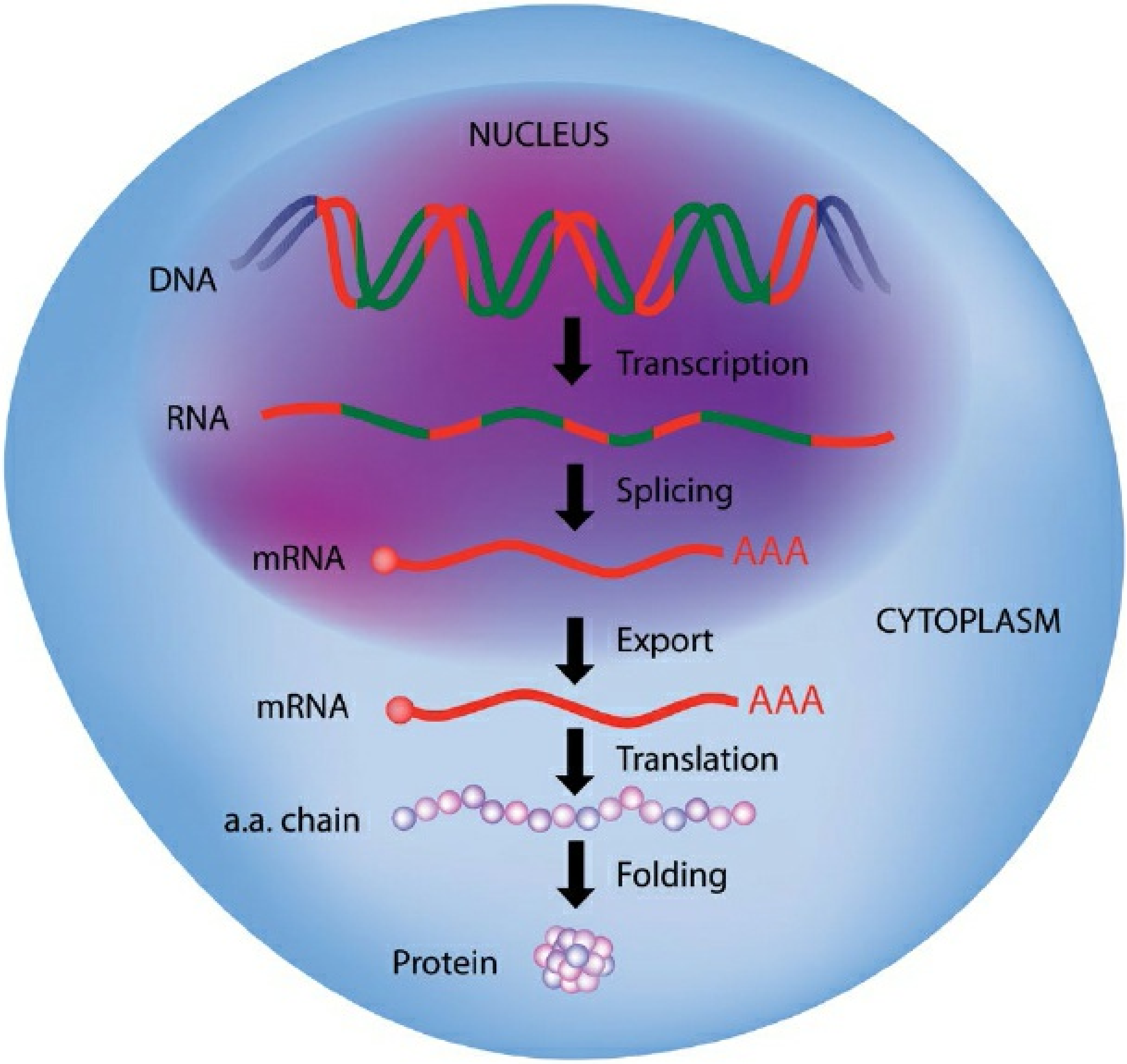
Information is "transcribed" from a section of DNA to a newly assembled piece of messenger RNA (mRNA); mRNA makes a copy of one of the two strands of DNA, which serves as a template. The mRNA then travels from the nucleus to the cytoplasm where it binds to a ribosome. The ribosome translates the instructions as a codon, a three nucleotide sequence that spells out the order in which amino acids are to be added to the growing peptide chain. The final step involves the faithful replication of DNA to a daughter cell, carried out by the process of mitosis.

As originally formulated, the sequence was never translated backwards from DNA to RNA. When the enzyme *reverse transcriptase* was independently discovered in 1970 by Howard Temin at the University of Wisconsin-Madison and David Baltimore at MIT, this upset the premise of the central dogma. For this work, Temin and Baltimore were co-recipients of the 1975 Nobel Prize. Subsequently, it was found that reverse transcriptase is present in retroviruses, such as the human immunodeficiency virus (HIV), and converts DNA from RNA. In addition, and as another exception to the central dogma, not all DNA is involved in programming the synthesis of proteins. Some 98 percent of human DNA is noncoding DNA (dubbed "junk DNA"); its biological function has not yet been determined.

Semantic issues were also raised. In his 1988 autobiography, *What Mad Pursuit: A Personal View of Scientific Discovery*, Crick commented that the term "dogma" was ill-advised. He chose not to use the word "hypothesis," which, in retrospect, would have been far more appropriate. Dogma is a belief that cannot be doubted—certainly not the case when used here.

SEE ALSO DNA Structure (1953), Ribosomes (1955), Cracking the Genetic Code for Protein Biosynthesis (1961), Epigenetics (1983).

This image depicts the flow of genetic instructions from DNA, to RNA, to the production of amino acids, which link together to form proteins.


NUCLEUS
DNA
Transcription
RNA
Splicing
mRNA
AAA
CYTOPLASM
Export
mRNA
AAA
Translation
a.a. chain
Folding
Protein

1958

Integrated Circuit • *Clifford A. Pickover*

Jack St. Clair Kilby (1923–2005), **Robert Norton Noyce** (1927–1990)

"It seems that the integrated circuit was destined to be invented," writes technology-historian Mary Bellis. "Two separate inventors, unaware of each other's activities, invented almost identical integrated circuits, or ICs, at nearly the same time."

In electronics, an IC, or microchip, is a miniaturized electronic circuit that relies upon semiconductor devices and is used today in countless examples of electronic equipment, ranging from coffeemakers to fighter jets. The conductivity of a semiconductor material can be controlled by introduction of an electric field. With the invention of the monolithic IC (formed from a single crystal), the traditionally separate transistors, resistors, capacitors, and all wires could now be placed on a single crystal (or chip) made of semiconductor material. Compared with the manual assembly of discrete circuits of individual components, such as resistors and transistors, an IC can be made more efficiently using the process of photolithography, which involves selectively transferring geometric shapes on a mask to the surface of a material such as a silicon wafer. The speed of operations is also higher in ICs because the components are small and tightly packed.

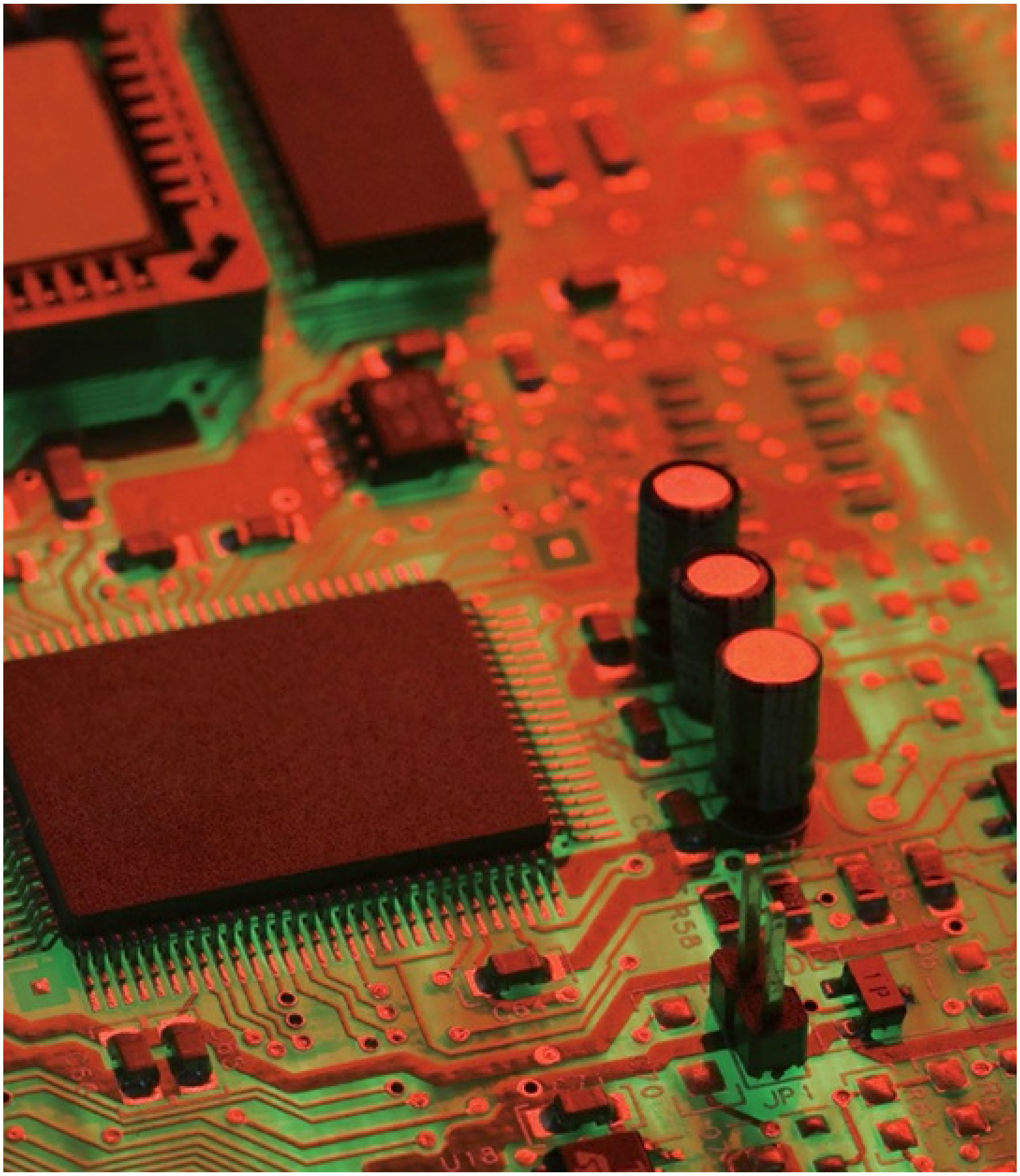
Physicist Jack Kilby invented the IC in 1958. Working independently, physicist Robert Noyce invented the IC six months later. Noyce used silicon for the semiconductor material, and Kilby used germanium. Today, a postage-stamp-sized chip can contain over a billion transistors. The advances in capability and density—and decrease in price—led technologist Gordon

Moore to say, “If the auto industry advanced as rapidly as the semiconductor industry, a Rolls Royce would get a half a million miles per gallon, and it would be cheaper to throw it away than to park it.”

Kilby invented the IC as a new employee at Texas Instruments during the company’s late-July vacation time when the halls of his employer were deserted. By September, Kilby had built a working model, and on February 6, Texas Instruments filed a patent.

SEE ALSO Transistor (1845), ENIAC (1946), Quantum Computers (1981).

The exterior packaging of microchips (e.g., large rectangular shape at left) house the integrated circuits inside that contain the tiny components such as transistor devices. The housing protects the much smaller integrated circuit and provides a means of connecting the chip to a circuit board.


R58
JP1
U18

1959

Structure of Antibodies • *Clifford A. Pickover*

Paul Ehrlich (1854–1915), **Rodney Robert Porter** (1917–1985), **Gerald Maurice Edelman** (1929–2014)

The **germ theory of disease**, proposed in the mid-1800s, suggested that microorganisms cause many diseases, and people wondered how the body attempted to defend itself against such foreign invaders. Today, we know that antibodies (also called immunoglobulins) are the protective proteins that circulate in our bodies and identify and neutralize foreign substances, called antigens, which include bacteria, viruses, parasites, transplanted foreign tissues, and venoms. Antibodies are produced by plasma B cells (a kind of white blood cell). Each antibody consists of two heavy chains and two light chains made of amino acids. These four chains are bound together to form a molecule shaped like the letter Y. Variable regions at the two upper tips of the Y bind to antigens, thereby marking them for other parts of the immune system to destroy. Many millions of different antibodies can exist with slightly different tip structures. Antibodies can also neutralize antigens directly by binding to them and, for example, preventing the pathogens from entering or damaging cells.

Antibodies circulating in the blood play a role in the humoral immune system. Additional immune players—phagocytes—function like single-celled creatures that engulf and destroy smaller particles. The binding of antibodies to an invader can mark the invader for ingestion by phagocytes.

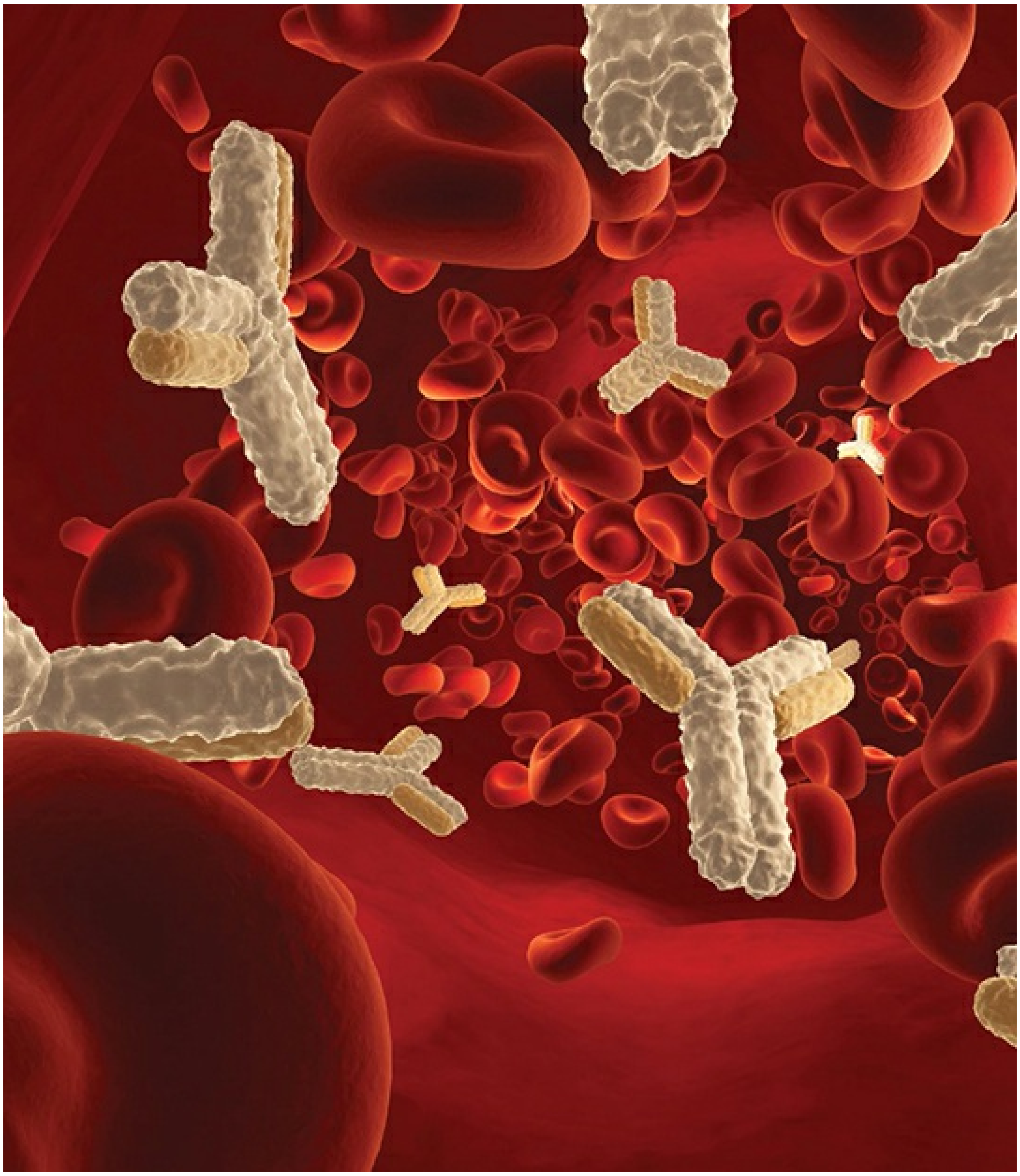
Tests used to detect particular antibodies may lead a physician to suspect, or rule out, certain diseases such as Lyme disease. Autoimmune disorders may be triggered by antibodies binding to the body's own healthy cells.

Antiserums can sometimes be made by injecting animals with an antigen and then isolating the antibodies in the serum for use in humans.

Paul Ehrlich coined the word *antibody* (*Antikörper* in German) around 1891, and he proposed a mechanism in which the receptors on cells attached to toxins in a tight lock-and-key fit to trigger antibody production. English biochemist Rodney Porter and American biologist Gerald Edelman won the 1972 Nobel Prize for their independent research, which started around 1959 and elucidated the antibody's Y-like structure, as well as identifying heavy and light chains.

SEE ALSO Smallpox Vaccine (1798), Germ Theory of Disease (1862), Discovery of Viruses (1892).

Artist's concept of Y-shaped antibodies circulating through the bloodstream.



1960

Laser • *Clifford A. Pickover*

Albert Einstein (1879–1955), **Leon Goldman** (1905–1997), **Charles Hard Townes** (1915–2015), **Theodore Harold "Ted" Maiman** (1927–2007)

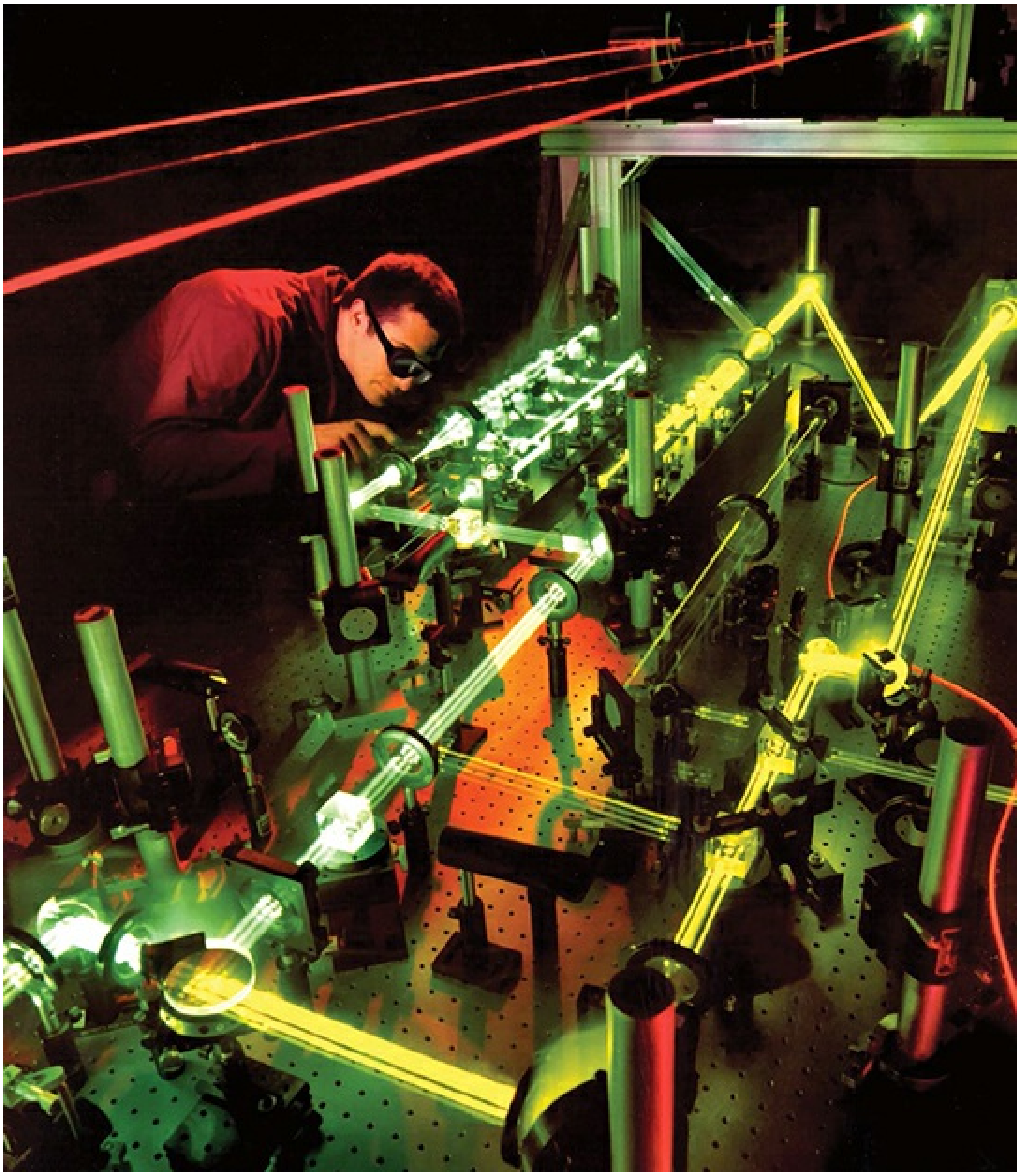
"Laser technology has become important in a wide range of practical applications," writes laser expert Jeff Hecht, "ranging from medicine and consumer electronics to telecommunications and military technology. . . . 18 recipients of the Nobel Prize received the award for laser-related research."

The word *laser* is an acronym for light amplification by stimulated emission of radiation, and lasers make use of a subatomic process known as stimulated emission, first considered by Albert Einstein in 1917. In stimulated emission, a photon (a particle of light) of the appropriate energy causes an electron to drop to a lower energy level, which results in the creation of another photon. This second photon is said to be coherent with the first and has the same phase, frequency, polarization, and direction of travel as the first photon. If the photons are reflected so that they repeatedly traverse the same atoms, an amplification can take place and an intense radiation beam is emitted. Lasers can be created so that they emit electromagnetic radiation of various frequencies.

In 1953, physicist Charles Townes and students produced the first microwave laser (maser), but it was not capable of continuous radiation emission. Theodore Maiman created the first practical working laser in 1960, using pulsed operation. In 1961, dermatologist Leon Goldman was first to use a laser to treat melanoma (a skin cancer), and related methods were later used for removing birthmarks and tattoos with minimal scarring. Because of the speed and precision of laser surgery, lasers have since been used in ophthalmology, dentistry, and many other fields. In LASIK eye surgery, a laser beam is used to change the shape of the eye's cornea to correct for nearsightedness and farsightedness. In prostate surgery, a laser may be used to vaporize tumors. Green laser light can be used for coagulation when the light is absorbed by hemoglobin to stop a bleeding blood vessel. The hot beam of a surgical laser can be used to cauterize, or seal off, open blood vessels as the beam moves along tissue.

SEE ALSO Sutures (c. 3000 BCE) Newton's Prism (1672), Wave Nature of Light (1801).

An optical engineer studies the interaction of several lasers for potential use aboard a laser-weapons system being developed to defend against ballistic missile attacks. The U.S. Directed Energy Directorate conducts research into beam-control technologies.



1961

Cracking the Genetic Code for Protein Biosynthesis • *Michael C. Gerald with Gloria E. Gerald*

George Gamow (1904–1968), **Francis Crick** (1916–2004), **Rosalind Franklin** (1920–1958), **Robert W. Holley** (1922–1993), **Har Gobind Khorana** (1922–2011), **Marshall Warren Nirenberg** (1927–2010), **James D. Watson** (b. 1928), **J. Heinrich Matthaei** (b. 1929)

The structure of DNA was determined in 1953 by Watson, Crick, and Franklin, with strands of the double helix consisting of four nucleotides: adenine (A), thymine (T), cytosine (C), and guanine (G); in RNA, uracil (U) replaces T. But how was the genetic information contained in the DNA molecule translated to the biosynthesis of a protein?

The Russian physicist George Gamow postulated that a three-letter nucleotide (codon) could define up to sixty-four amino acids, more than sufficient to code for all twenty amino acids used to build proteins. In 1961, Marshall Nirenberg, with J. Heinrich Matthaei at the National Institutes of Health, sought to determine what amino acid would be formed after a single nucleotide was added to a reaction mixture. UUU produced the amino acid phenylalanine, cracking the first letter in the genetic code. Shortly thereafter, the addition CCC was found to yield proline. Har Gobind Khorana at the University of Wisconsin-Madison produced more complex sequences composed of repeated two-nucleotide sequences, the first of which was

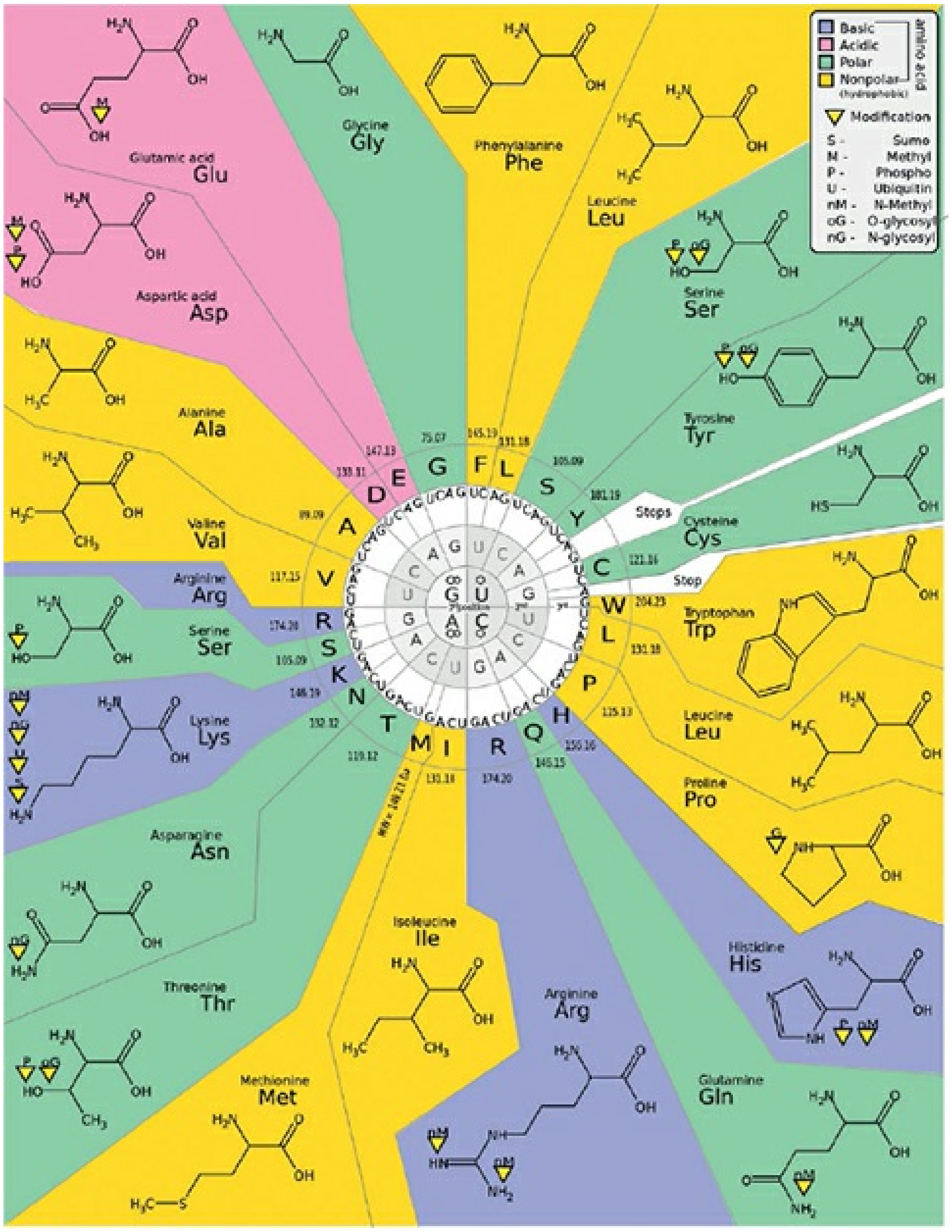
UCUCUC, read as serine-leucine-serine-leucine . . . ; subsequently, the remainder of the codons were determined.

In 1964, Robert Holley, at Cornell University, discovered and established the chemical structure of transfer RNA (tRNA), thus providing the link between the role of messenger RNA (mRNA) and ribosomes. The information needed to make a protein is first attached to tRNA and then translated to messenger mRNA in a ribosome. Each tRNA only recognizes one set of three nucleotides in mRNA, and tRNA binds to only one of the twenty amino acids. A protein is formed by the addition of one amino acid at a time. Nirenberg, Khorana, and Holley were jointly awarded the 1968 Nobel Prize.

Apart from variations, the genetic codes used by all forms of life are very similar. Based on the theory of evolution, the genetic code was established very early in the history of life.

SEE ALSO DNA Structure (1953), Ribosomes (1955), Central Dogma of Molecular Biology (1958), Human Genome Project (2003).

This image depicts the relationship between the codon (the three-letter nucleotide consisting of adenine, thymine, cytosine, and guanine or uracil) and the encoding of amino acids.



Basic
Acidic
Polar
Nonpolar (hydrophobic)
amino acid
Modification
S - Sumo
M - Methyl
P - Phospho
U - Ubiquitin
nM - N-Methyl
oG - O-glycosyl
nG - N-glycosyl
Glutamic acid Glu
Aspartic acid Asp
Glycine Gly
Phenylalanine Phe
Leucine Leu
Serine Ser
Tyrosine Tyr
Stops
Cysteine Cys
Stop
Tryptophan Trp
Leucine Leu
Proline Pro
Histidine His
Glutamine Gln
Arginine Arg
Isoleucine Ile
Methionine Met
Threonine Thr
Asparagine Asn
Lysine Lys
Serine Ser
Arginine Arg
Valine Val
Alanine Ala

1961

First Humans in Space • *Jim Bell*

Yuri Gagarin (1934–1968), **Alan Shepard** (1923–1998)

The Soviet Union’s successful launch of *Sputnik 1* in 1957 marked the beginning of the Space Age, as well as the beginning of an epic geopolitical race for technological, military, and moral superiority with the United States. The Russians had launched the first animal into space—a dog named Laika onboard *Sputnik 2*—and the US was launching monkeys and chimpanzees, but both governments knew that the next big victory in the space race could only be claimed by launching a person into space.

The Soviet human spaceflight program was called Vostok, and, like the original Sputnik effort, it was based on adapting existing intercontinental ballistic missile rockets to accommodate a small passenger capsule. About 20 Soviet Air Force pilots were secretly screened for the privilege of becoming the first cosmonauts (“space sailors” in Russian); the man chosen to be first was Senior Lieutenant Yuri Gagarin. At the same time, the US human spaceflight program, called Project Mercury, was on a parallel track, modifying the Redstone missile to accommodate its small single-passenger capsule. Seven test pilots, from the air force, navy, and marines, were ultimately selected and became instant celebrities, even before their flights. Navy test pilot Alan Shepard was chosen to fly the first *Mercury* mission.

Both Vostok and Mercury had early (unmanned) launch failures; both teams had to demonstrate that their rockets would work with an empty capsule before government leaders would authorize a human-piloted flight. Both teams were neck and neck in the race to launch a person first in early 1961, and once again the Soviets scored an enormous international victory by successfully sending Gagarin into space first, for one orbit of Earth in *Vostok*

1 on April 12, 1961. Three weeks later, Shepard became the second person—and first American—launched into space with his successful suborbital flight in the *Freedom 7* capsule.

The Russians had again taken the lead. But America upped the ante shortly after Shepard's flight, when president John F. Kennedy, in an address to Congress, called for NASA to land a man on the moon before the decade was out.

SEE ALSO Wright Brothers' Airplane (1903), Saturn V Rocket (1967), First on the Moon (1969).

Cosmonaut Yuri Gagarin preparing to board his Vostok 1 *spacecraft on the morning of April 12, 1961. Seated behind him was his backup, cosmonaut German Titov, who eventually piloted* Vostok 2 *in August 1961, becoming the second person to orbit the Earth.*

1961

Green Revolution • *Marshall Brain*

Norman Borlaug (1914–2009)

Between 1950 and 1987, world population doubled from 2.5 billion to 5 billion people. It was a startling surge. And humans were already putting a strain on food supplies. In 1943, for example, 4 million people in India (6 percent of the population) died in a famine.

During that period of surging population, there was a problem brewing: at then-current production levels, the world had no way to produce enough food to feed everyone. The process that prevented mass starvation—the development that saved a billion or more lives—began in 1961, and was called the Green Revolution. Biologists and engineers worked together to spread advanced agricultural technologies around the world, championed by American biologist and humanitarian Norman Borlaug, who became a spokesperson for these initiatives.

A big factor in improving food production happened at the biological level, by breeding and, later, genetically engineering better strains of cereal grains like wheat and rice. Biologists took an engineer's problem-solving approach—they were trying to breed plants that could make use of more nitrogen, while at the same time putting the nitrogen into grain production rather than stem construction. The biologists wanted short, stocky stems so the plants would not fall over. They also wanted to reduce the time to harvest. They were able to pull this off by finding and incorporating dwarf strains and other useful characteristics to create high-yield crops.

These new strains of plants needed water and fertilizer. Engineers could respond to those needs with irrigation projects and new ways of increasing fertilizer production. Then they went a step further: in warm climates it is possible to put in two crops a year, but only if there is enough water to support the second crop. With the rainy season supplying the water for one crop, a country like India needed a way to store water for the second crop. So engineers built thousands of new dams in India to catch the water from monsoon rains and hold it. Now India could grow twice as much food.

The effect of these improvements was startling. World food production doubled, then doubled again. Even though population was growing, the food supply grew faster. Science and engineering together created a farming revolution.

SEE ALSO Agriculture (c. 10,000 BCE), Domestication of Animals (c. 10,000 BCE), Rice Cultivation (c. 7000 BCE) Photosynthesis (1947).

The engineering innovations that came about as a result of the Green Revolution were numerous, and included new strains of rice meant to create higher yields for famine-stricken regions.

1961

Standard Model • *Clifford A. Pickover*

Murray Gell-Mann (b. 1929), **Sheldon Lee Glashow** (b. 1932), **George Zweig** (b. 1937)

"Physicists had learned, by the 1930s, to build all matter out of just three kinds of particle: electrons, neutrons, and protons," author Stephen Battersby writes. "But a procession of unwanted extras had begun to appear—neutrinos, the positron and antiproton, pions and muons, and kaons, lambdas and sigmas—so that by the middle of the 1960s, a hundred supposedly fundamental particles have been detected. It was a mess."

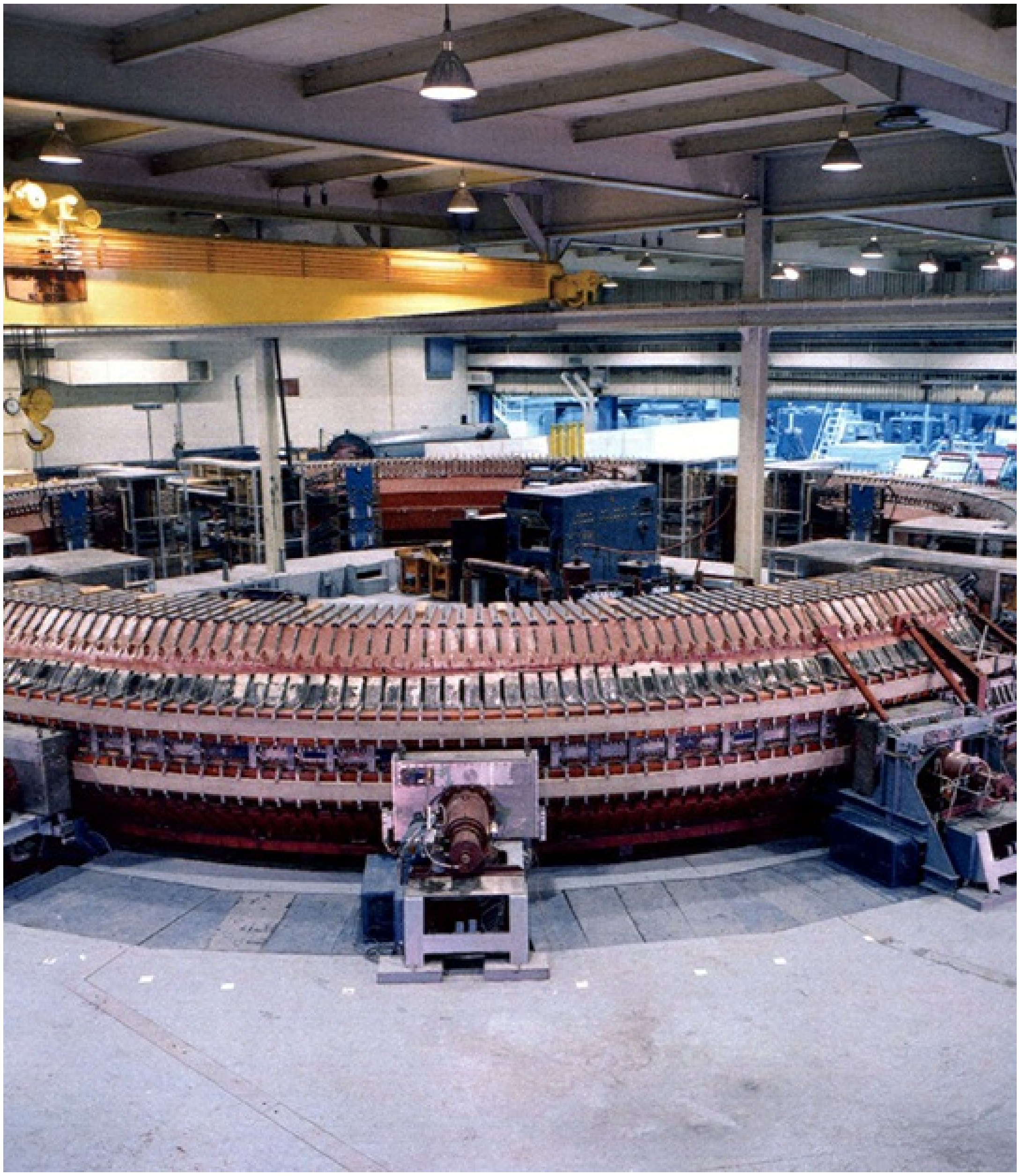
Through a combination of theory and experiment, a mathematical model called the Standard Model explains most of particle physics observed so far by physicists. According to the model, elementary particles are grouped into two classes: *bosons* (e.g., particles that often transmit forces) and *fermions*. Fermions include various kinds of Quarks (3 quarks make up both the proton and Neutrons) and leptons (such as the Electron and Neutrino, the latter of which was discovered in 1956). Neutrinos are very difficult to detect because they have a minute (but not zero) mass and pass through ordinary matter almost undisturbed. Today, we know about many of these subatomic particles by smashing apart atoms in particle accelerators and observing the resulting fragments.

As suggested, the Standard Model explains forces as resulting from matter particles exchanging boson force-mediating particles that include photons and gluons. The Higgs particle is the fundamental particle predicted by the Standard Model that explains why other elementary particles have masses. The force of gravity is thought to be generated by the exchange of massless gravitons, but these have not yet been experimentally detected. In fact, the Standard Model is incomplete, because it does not include the force of gravity. Some physicists are trying to add gravity to the Standard Model to produce a grand unified theory, or GUT.

In 1964, physicists Murray Gell-Mann and George Zweig proposed the concept of quarks, just a few years after Gell-Mann's 1961 formulation of a particle classification system known as the Eightfold Way. In 1960, physicist Sheldon Glashow's unification theories provided an early step toward the Standard Model.

SEE ALSO String Theory (1919), Neutron (1932), Quarks (1964), Theory of Everything (1984), Large Hadron Collider (2009).

The Cosmotron. This was the first accelerator in the world to send particles with energies in the billion electron volt, or GeV, region. The Cosmotron synchrotron reached its full design energy of 3.3 GeV in 1953 and was used for studying subatomic particles.



1963

Chaos and the Butterfly Effect • *Clifford A. Pickover*

Jacques Salomon Hadamard (1865–1963), **Jules Henri Poincaré** (1854–1912), **Edward Norton Lorenz** (1917–2008)

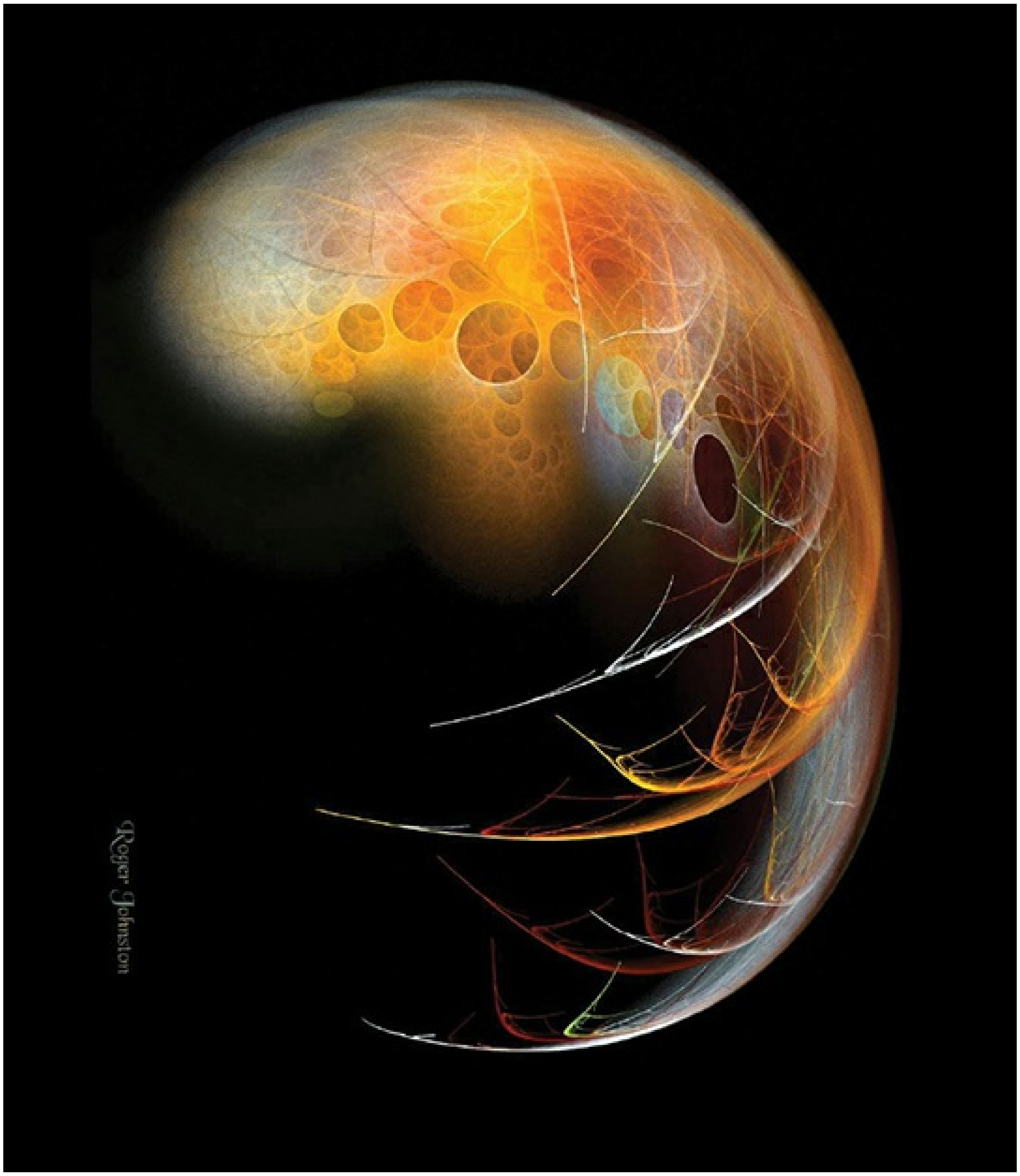
To ancient humans, chaos represented the unknown, the spirit world—menacing, nightmarish visions that reflected man's fear of the uncontrollable and the need to give shape and structure to his apprehensions. Today, chaos theory is an exciting, growing field that involves the study of wide-ranging phenomena exhibiting a sensitive dependence on initial conditions. Although chaotic behavior often seems "random" and unpredictable, it often obeys strict mathematical rules derived from equations that can be formulated and studied. One important research tool to aid in the study of chaos is computer graphics. From chaotic toys with randomly blinking lights to wisps and eddies of cigarette smoke, chaotic behavior is generally irregular and disorderly; other examples include weather patterns, some neurological and cardiac activity, the stock market, and certain electrical networks of computers. Chaos theory has also often been applied to a wide range of visual art.

In science, certain famous and clear examples of chaotic physical systems exist, such as thermal convection in fluids, panel flutter in supersonic aircraft, oscillating chemical reactions, fluid dynamics, population growth, particles impacting on a periodically vibrating wall, various pendula and rotor motions, nonlinear electrical circuits, and buckled beams.

The early roots of chaos theory started around 1900 when mathematicians such as Jacques Hadamard and Henri Poincaré studied the complicated trajectories of moving bodies. In the early 1960s, Edward Lorenz, a research meteorologist at the Massachusetts Institute of Technology, used a system of equations to model convection in the atmosphere. Despite the simplicity of his formulas, he quickly found one of the hallmarks of chaos—that is, extremely minute changes of the initial conditions led to unpredictable and different outcomes. In his 1963 paper, Lorenz explained that a butterfly flapping its wings in one part of the world could later affect the weather thousands of miles away. Today, we call this sensitivity the *butterfly effect*.

SEE ALSO Gödel’s Theorem (1931), Cellular Automata (1952), Fractals (1975).

Chaotic mathematical pattern, created by Roger A. Johnston. Although chaotic behavior may seem “random” and unpredictable, it often obeys mathematical rules derived from equations that can be studied. Very small changes of the initial conditions can lead to very different outcomes.


Roger Johnston

1963

Cognitive Behavioral Therapy • *Clifford A. Pickover*

Epictetus (55–135), **Albert Ellis** (1913–2007), **Aaron Temkin Beck** (b. 1921)

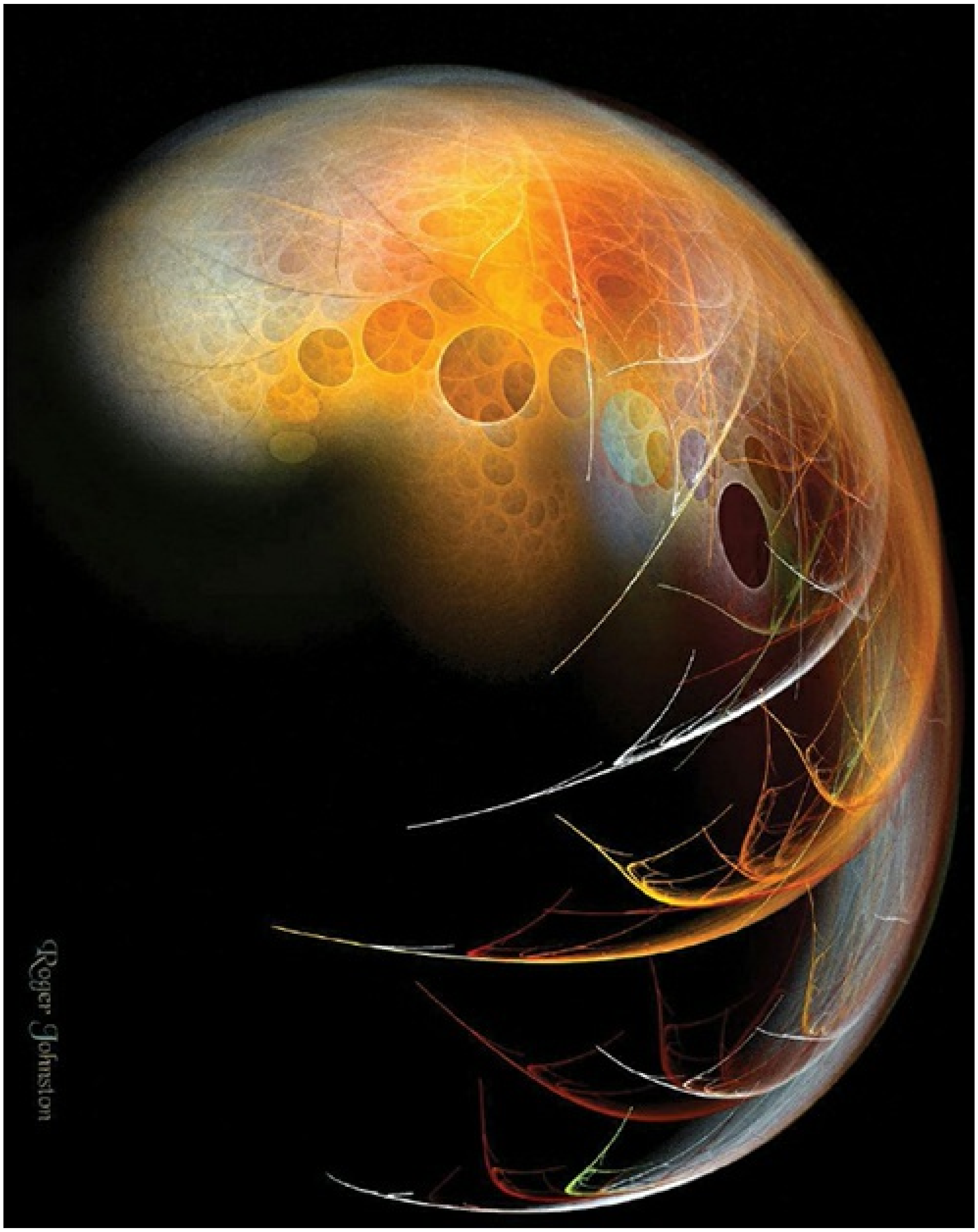
Cognitive behavioral therapy (CBT), which emphasizes the role of errors in thinking in producing negative emotions, has ancient roots. The Greek Stoic philosopher Epictetus wrote in the *Enchiridion*, “Men are disturbed not by things, but by the view which they take of them.” In CBT, the psychotherapist helps the patient think about situations and circumstances in new ways, in order to change patients’ reactions and feelings. If the patient can identify maladaptive or irrational thoughts, the thoughts can be challenged. The resultant improved behaviors serve to educate the patient further and to reinforce the more productive way of thinking. A patient commonly keeps a diary of events and associated feelings and thoughts.

In the 1950s, American psychoanalyst Albert Ellis shaped the development of CBT, partly because of his dislike of the seemingly inefficient and indirect nature of classical psychoanalysis. Ellis wanted the therapist to be heavily involved in helping the client modify unhelpful patterns of thought. In the 1960s, American psychiatrist and psychoanalyst Aaron Beck became the major driving force behind modern CBT.

CBT has often been shown to be helpful in many cases of depression, insomnia, anxiety, obsessive-compulsive disorder, post-traumatic stress disorder, eating disorders, chronic pain, and schizophrenia. When seeing a therapist, a patient is sometimes asked to reframe a thought in terms of a hypothesis that can be tested. In this manner, the patient can “step back” from the belief to allow more objective examination and arrive at a different view. For example, a depressed person may overgeneralize, concluding she will never get a job after a single failed interview. For phobias and compulsions, symptoms are sometimes decreased by gradual exposure to a fearful stimulus. Depressed people may be asked to schedule small pleasurable activities (e.g., meet a friend for coffee). Not only does this modify behavior, but it can be used to test a belief or hypothesis such as “No one enjoys my company.” CBT can also be used in conjunction with medications for very serious psychological disorders.

SEE ALSO *The Principles of Psychology* (1890), Psychoanalysis (1899), Classical Conditioning (1903), Antidepressant Medications (1957), Theory of Mind (1978).

Using CBT and controlled, gradual exposure to spiders, a therapist can often treat arachnophobia. Functional magnetic resonance imaging studies suggest that CBT can affect the brain in a variety of useful ways.


Roger Johnston

1964

Brain Lateralization • *Michael C. Gerald with Gloria E. Gerald*

Wilder Penfield (1891–1976), **Herbert Jasper** (1906–1999), **Roger Wolcott Sperry** (1913–1994), **Michael Gazzaniga** (b. 1939)

In the 1940s, at McGill University's Montreal Neurological Institute, the famed Canadian neurosurgeon Wilder Penfield was treating severely epileptic patients by surgically destroying specific brain areas from which the seizure was thought to originate. Prior to operating, he applied very slight electrical stimulation to discrete regions of the motor and sensory cortex and, with his colleague, the neurologist Herbert Jasper, mapped the body part that responded to stimulation. Together, they constructed a homunculi ("little man") map representing specific parts of the body affected by motor and sensory brain sites.

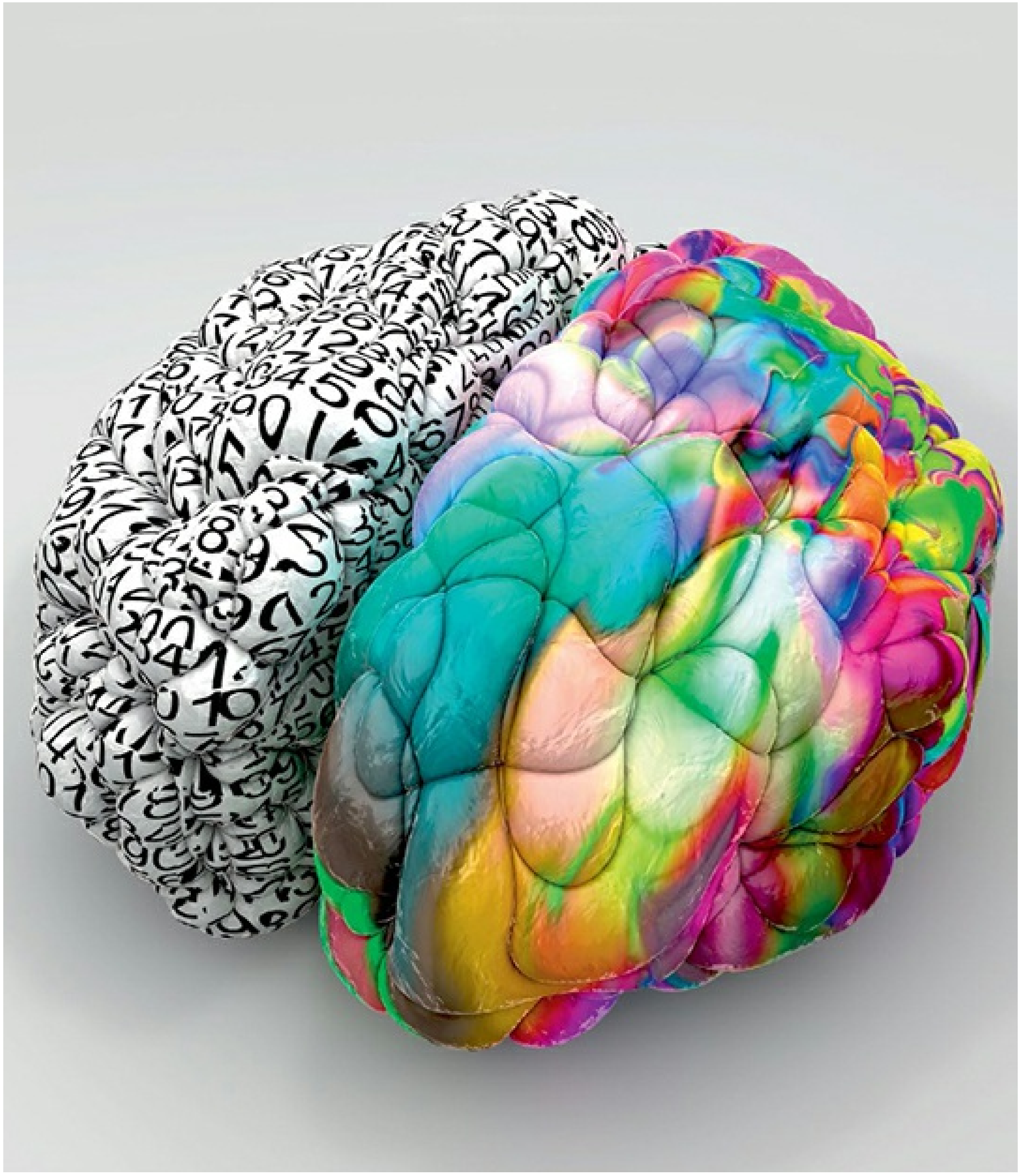
Studies conducted at the California Institute of Technology during the 1960s provided greater insight into brain lateralization (functional specialization). The left and right cerebral hemispheres (sides) of the brain are almost identical in appearance and yet are very different in carrying out functions. The two hemispheres normally communicate with each other through a thick band of nerve fibers called the *corpus callosum*. Since the 1940s, large portions of this band had been severed to treat severe epilepsy, resulting in split-brain patients; these operations are now rare. The psychobiologist Roger Sperry and his graduate student Michael Gazzaniga tested the functioning of each hemisphere independent of the other in split-brain humans and monkeys. In about 1964, they found that while each hemisphere was able to learn, one hemisphere had no perception of what the other hemisphere learned or experienced.

The results of these studies led to the conclusion that the left and right hemispheres are specialized in performing different functions. The left brain is primarily concerned with analytical, verbal, and language-processing tasks, while the right side handles the senses, creativity, feelings and facial recognition. Sperry was awarded the 1981 Nobel Prize for his split-brain discoveries.

Individuals are often characterized as being left-brain or right-brain thinkers. Left-brain persons are said to be more logical, fact-oriented, linear thinkers, and concerned with structure and reasoning, while those labeled as being right-brained are said to be feelings-oriented, intuitive, creative, and musical. Although this makes for interesting conversation at cocktail parties, there is no compelling anatomical or physiological evidence to support these labels, and most scientists regard this characterization as a myth.

SEE ALSO Cerebral Localization (1861), Neuron Doctrine (1891), Psychoanalysis (1899).

The left brain is said to control analytical, structured thinking, while the right brain is believed to influence creativity. This left-brain, right-brain distinction is popular but has generally been discounted by neuroscientists.



1964

Quarks • *Clifford A. Pickover*

Murray Gell-Mann (b. 1929), **George Zweig** (b. 1937)

Welcome to the particle zoo. In the 1960s, theorists realized that patterns in the relationships between various elementary particles, such as protons and neutrons, could be understood if these particles were not actually elementary but rather were composed of smaller particles called quarks.

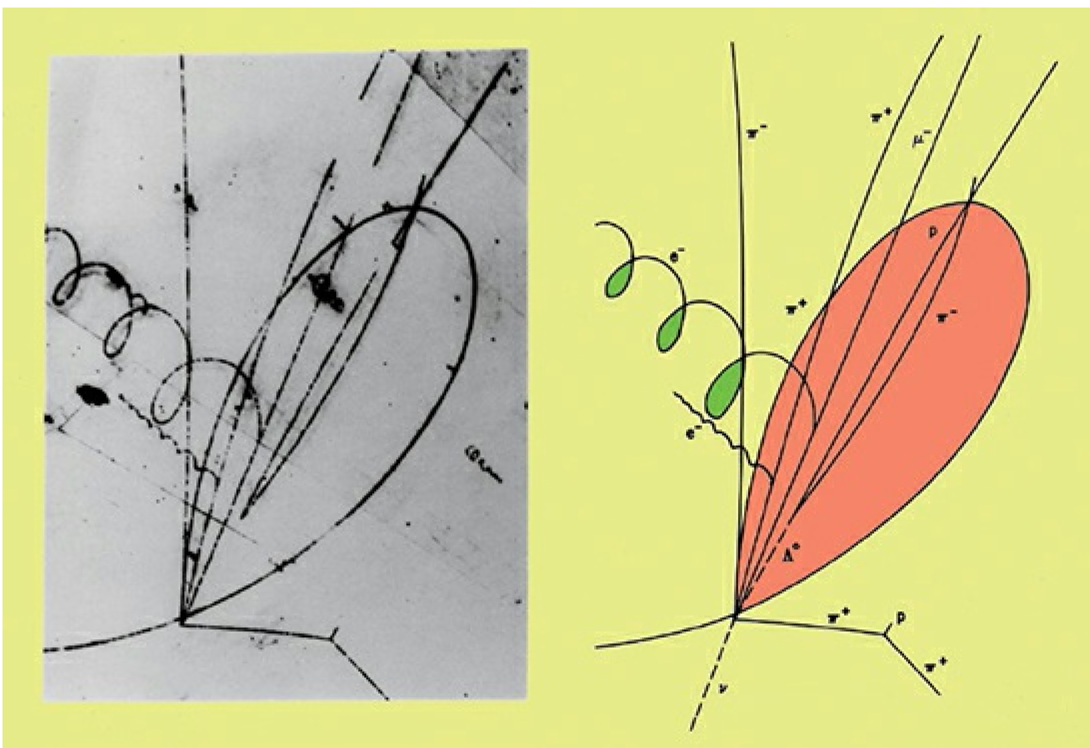
Six types, or *flavors*, of quarks exist and are referred to as *up*, *down*, *charm*, *strange*, *top* and *bottom*. Only the up and down quarks are stable, and they are the most common in the universe. The other heavier quarks are produced in high-energy collisions. (Note that another class of particles called leptons, which include electrons, are not composed of quarks.)

Quarks were independently proposed by physicists Murray Gell-Mann and George Zweig in 1964, and, by 1995, particle-accelerator experiments had yielded evidence for all six quarks. Quarks have fractional electric charge; for example, the up quark has a charge of +2/3, and the down quark has a charge of −1/3. Neutrons (which have no charge) are formed from two down quarks and one up quark, and the proton (which is positively charged) is composed of two up quarks and one down quark. The quarks are tightly bound together by a powerful short-range force called the color force, which is mediated by force-carrying particles called gluons. The theory that describes these strong interactions is called *quantum chromodynamics*. Gell-Mann coined the word *quark* for these particles after one of his perusals of the silly line in *Finnegans Wake*, "Three quarks for Muster mark."

Right after the Big Bang, the universe was filled with a quark-gluon plasma, because the temperature was too high for hadrons (i.e. particles like protons and neutrons) to form. Authors Judy Jones and William Wilson write, "Quarks pack a mean intellectual wallop. They imply that nature is three-sided. . . . Specks of infinity on the one hand, building blocks of the universe on the other, quarks represent science at its most ambitious—also its coyest."

SEE ALSO Electron (1897), Neutron (1932), Quantum Electrodynamics (1948), Standard Model (1961).

Scientists used the photograph (left) of particle trails in a Brookhaven National Laboratory bubble chamber as evidence for the existence of a charmed baryon (a three-quark particle). A neutrino enters the picture from below (dashed line in right figure) and collides with a proton to produce additional particles that leave behind trails.



1965

Cosmic Microwave Background •

Clifford A. Pickover

Arno Allan Penzias (b. 1933), **Robert Woodrow Wilson** (b. 1936)

The cosmic microwave background (CMB) is electromagnetic radiation filling the universe, a remnant of the dazzling “explosion” from which our universe evolved during the Big Bang 13.7 billion years ago. As the universe cooled and expanded, there was an increase in wavelengths of high-energy photons (such as in the gamma-ray and X-ray portion of the electromagnetic spectrum) and a shifting to lower-energy microwaves.

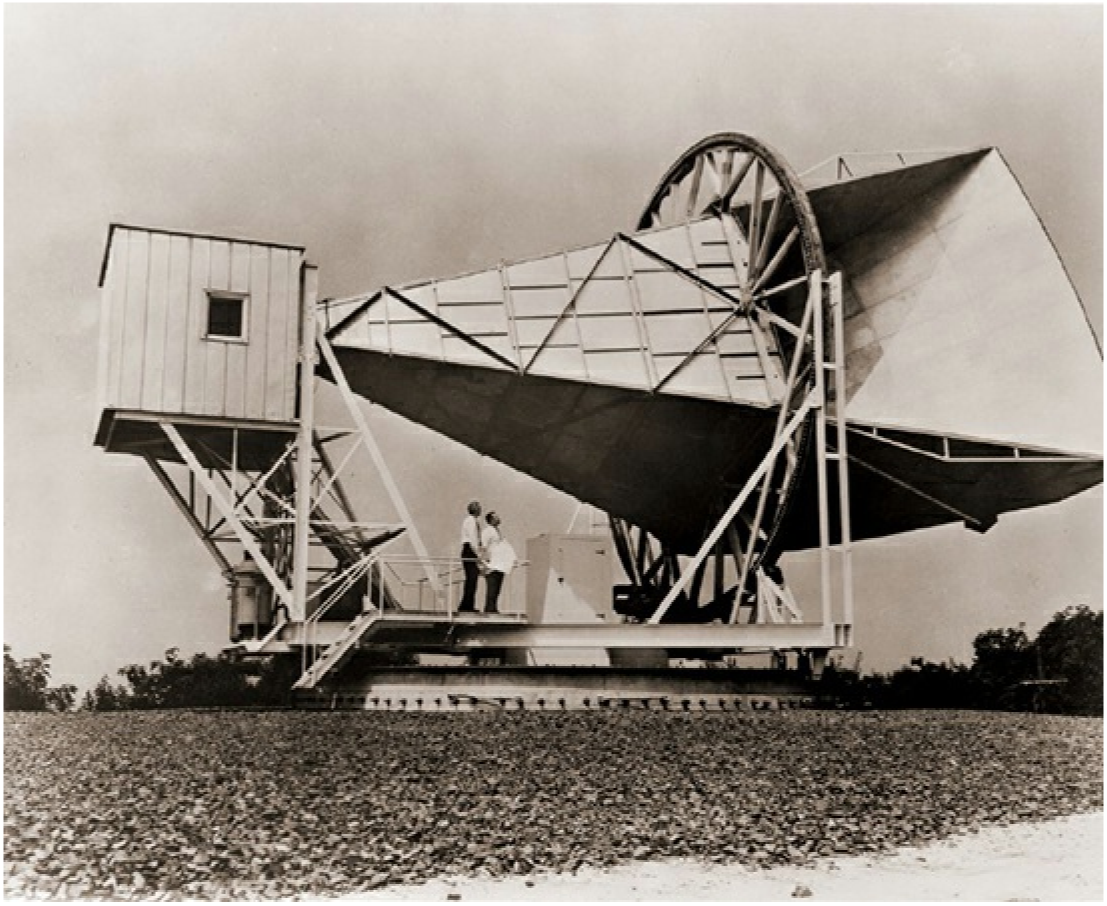
Around 1948, cosmologist George Gamow and colleagues suggested that this microwave background radiation might be detectable, and in 1965 physicists Arno Penzias and Robert Wilson of the Bell Telephone Laboratories in New Jersey measured a mysterious excess microwave noise that was associated with a thermal radiation field with a temperature of about −454 ºF (3 K). After checking for various possible causes of this background “noise,” including pigeon droppings in their large outdoor detector, it was determined that they were really observing the most ancient radiation in the universe and providing evidence for the Big Bang model. Note that because photons of energy take time to reach the Earth from distant parts of the universe; whenever we look outward in space, we are also looking back in time.

More precise measurements were made by the COBE (Cosmic Background Explorer) satellite, launched in 1989, which determined a temperature of -454.47 ºF (2.735 K). COBE also allowed researchers to measure small fluctuations in the intensity of the background radiation, which corresponded to the beginning of structures, such as galaxies, in the universe.

Luck matters for scientific discoveries. Author Bill Bryson writes, “Although Penzias and Wilson had not been looking for the cosmic background radiation, didn’t know what it was when they had found it, and hadn’t described or interpreted its character in any paper, they received the 1978 Nobel Prize in physics.” Connect an antenna to an analog TV; make sure it’s not tuned to a TV broadcast and “about 1 percent of the dancing static you see is accounted for by this ancient remnant of the Big Bang. The next time you complain that there is nothing on, remember you can always watch the birth of the universe.”

SEE ALSO Telescope (1608), Electromagnetic Spectrum (1864), X-rays (1895), Hubble’s Law of Cosmic Expansion (1929), Cosmic Inflation (1980).

The Horn reflector antenna at Bell Telephone Laboratories in Holmdel, New Jersey, was built in 1959 for pioneering work related to communication satellites. Penzias and Wilson discovered the cosmic microwave background using this instrument.



1966

Dynamic RAM • *Marshall Brain*

Robert Dennard (b. 1932)

Every computer needs RAM, or random access memory. The central processing unit of the computer needs a place to store its programs and data so it can access them quickly—at the same pace that the CPU's clock is operating. For each instruction the CPU (central processing unit) executes, it must fetch the instruction from RAM. The CPU also moves data to or from RAM.

Imagine you are an engineer looking at computer memory options in the late 1960s. There are two possibilities. The first is core memory, which is made by weaving tiny ferrite donuts into a wire mesh. The problems with core memory are many; it is expensive, heavy, and enormous. The second possibility is static RAM made from standard transistor circuits. It takes several transistors for each memory bit, and given the state of integrated circuits at the time, it is not possible to put much memory on a chip.

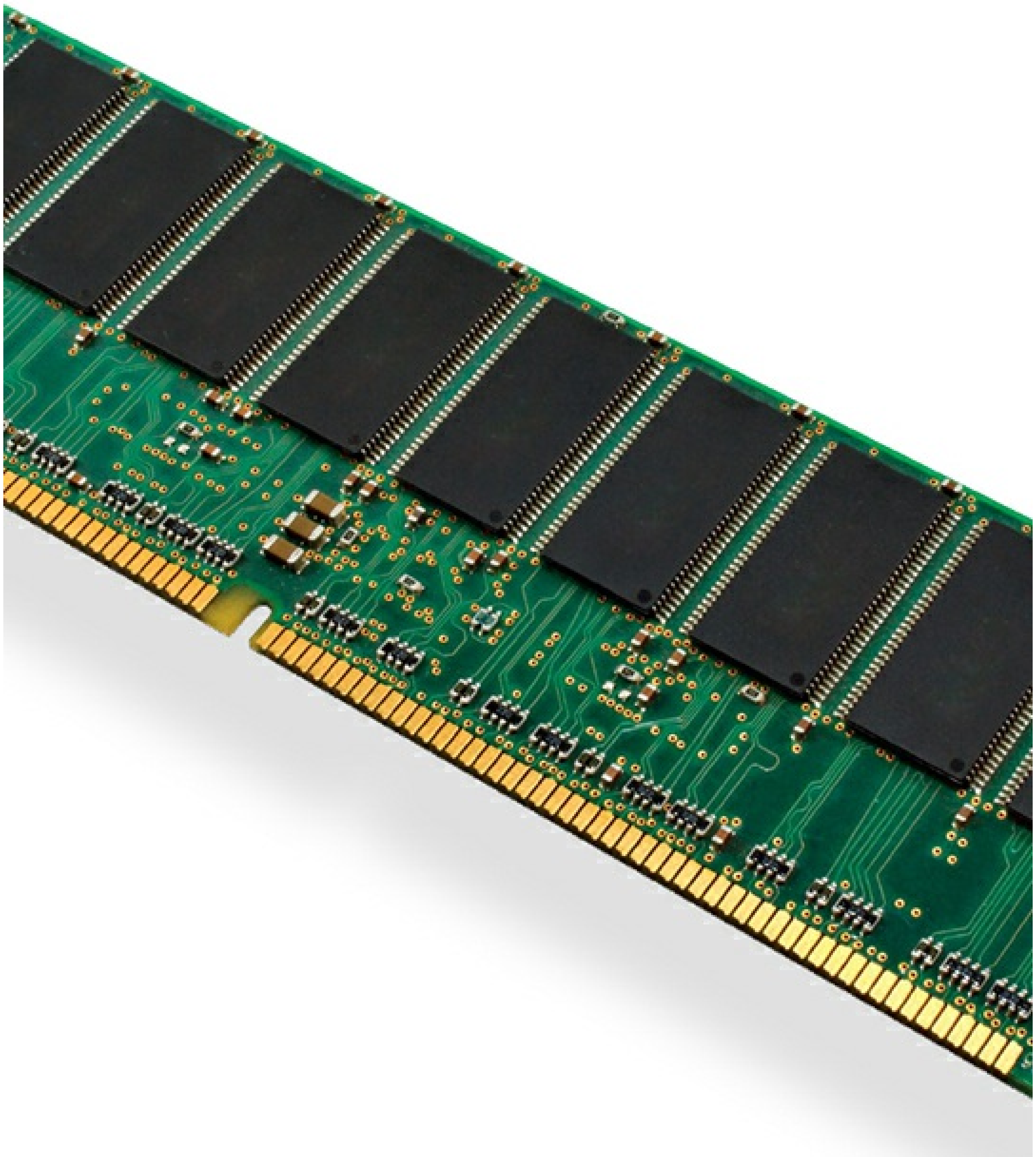
But in 1966, American electrical engineer Robert Dennard, working for IBM, tried something different in the interest of reducing the number of transistors and fitting more memory cells on a chip. He explored the idea of dynamic RAM using a capacitor to store one bit of data. When the capacitor is charged it represents a 1, discharged it represents a zero. On the surface this seems ridiculous, because capacitors leak. If you store a 1 in memory made of capacitors and do nothing, the capacitor will leak and forget the 1 in less than a tenth of a second.

But the advantage is that this approach greatly reduces the number of transistors, and therefore increases the number of memory cells on a chip. To solve the leakage problem, all of the capacitors are read periodically (for example, every few milliseconds) and rewritten, thus refilling all of the leaking capacitors containing 1s with a full charge. This approach is known as dynamic RAM (DRAM), first manifested in 1970, because it must be dynamically refreshed to keep the capacitors charged.

The dynamic RAM approach yields memory cells that are so much smaller, and therefore less expensive, than static RAM that every desktop, laptop, tablet, and smart phone today uses DRAM. It is a great example of the way engineers can reduce costs by embracing ideas that may seem initially ridiculous.

SEE ALSO Slide Rule (1621), Babbage Mechanical Computer (1822), ENIAC (1946), Transistor (1947).

Pictured: Dynamic SDRAM (synchronous dynamic random-access memory) for a computer.



1967

Endosymbiont Theory • *Michael C. Gerald with Gloria E. Gerald*

Konstantin Mereschkowski (1855–1921), **Lynn Margulis** (1938–2011)

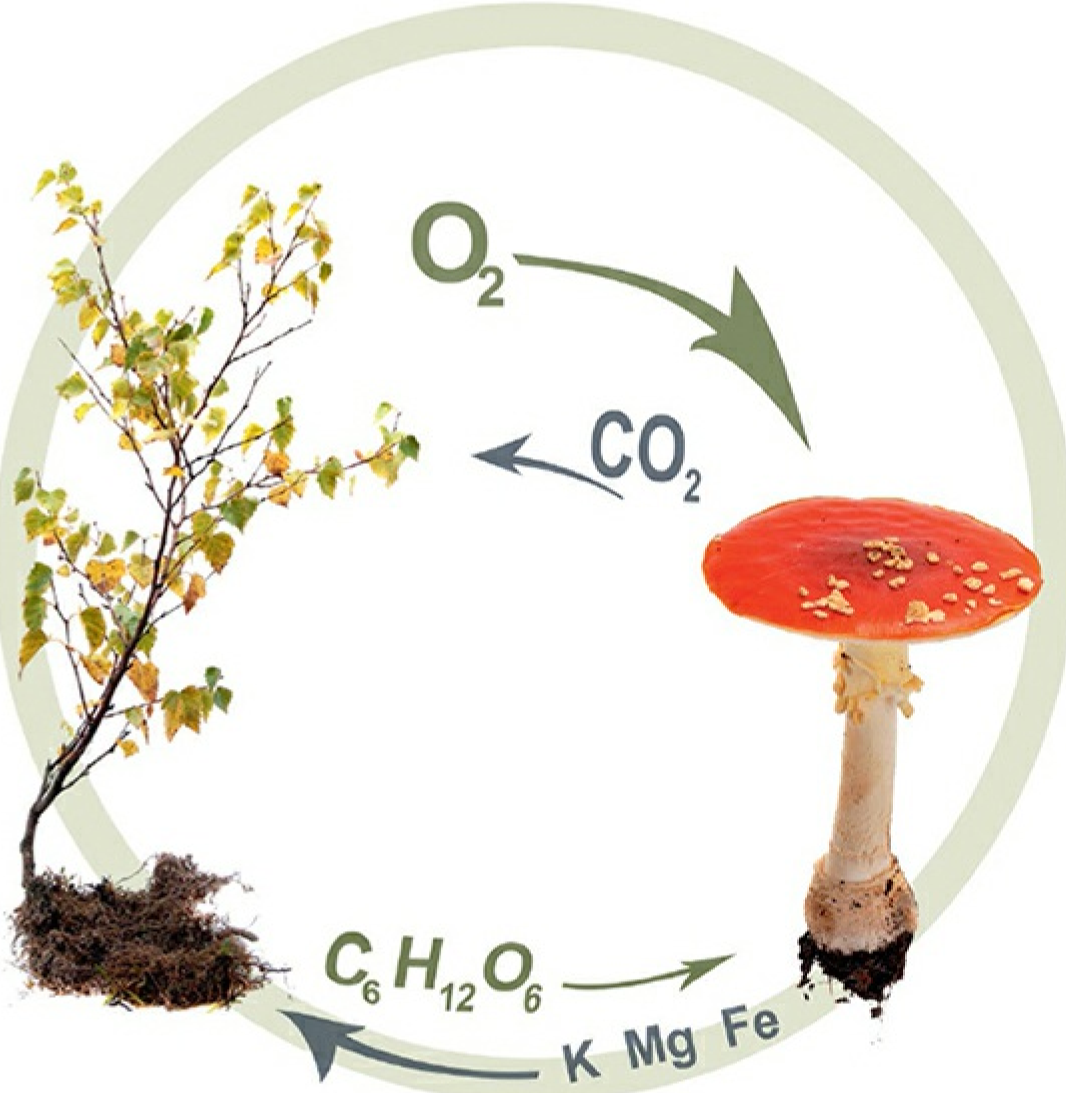
The endosymbiont theory helps us understand evolution because it explains the origin of organelles in eukaryotic cells—those in plants, animals, fungi, and protists. Symbiosis, which occurs at all levels of biological organization, involves two organisms that cooperate for their mutual benefit to gain a competitive advantage—for example, insect pollination of flowers or the digestion of food by gut bacteria. In eukaryotic cells, mitochondria and chloroplasts are organelles involved in the generation of energy required to carry out cell functions. Mitochondria, the site of cellular respiration, use oxygen to break down organic molecules to form ATP (adenosine triphosphate), while chloroplasts in plants—the sites of photosynthesis—use energy derived from the sun to synthesize glucose from carbon dioxide and water.

ADDING ONE ORGANELLE AT A TIME. According to the endosymbiont theory, small bacteria (alpha proteobacteria) containing mitochondria were engulfed by primitive eukaryotic cells (protists). In the ensuing symbiotic relationship, the bacterium (now called the *symbiont*) provided its evolving mitochondria, the generator of energy, while the eukaryotic cell offered protection and nutrients. By an analogous process, a eukaryotic cell engulfed a photosynthetic cyanobacterium that, in time, evolved into a chloroplast. In this description of primary endosymbiosis, one living organism has been engulfed by another. When the product of this primary endosymbiosis is engulfed by another eukaryote, secondary endosymbiosis is said to have occurred. This provides the basis for incorporating additional organelles and expands the number of environments in which eukaryotes can survive.

The endosymbiotic theory was first proposed in 1905 for chloroplasts by the Russian botanist Konstantin Mereschkowski (who rejected Darwin's theory of evolution and actively promoted eugenics); the idea was expanded to include mitochondria in 1920. Endosymbiotic theory gained no scientific traction until 1967, when it was reintroduced by Lynn Margulis, a biology professor at the University of Massachusetts, Amherst (and former wife of the late astronomer Carl Sagan). Her paper was rejected by fifteen journals before being accepted, and is now considered a milestone in endosymbiont theory.

SEE ALSO Natural Section (1859), Cellular Respiration (1937), Photosynthesis (1947).

This image depicts the symbiosis between a fly agaric mushroom (Amanita muscaria) *and a birch tree. The mushroom receives sugar ($C_6H_{12}O_6$) and oxygen from the tree in exchange for minerals and carbon dioxide.*


O_2
CO_2
$C_6H_{12}O_6$
K Mg Fe

1967

Heart Transplant • *Clifford A. Pickover*

James D. Hardy (1918–2003), **Christiaan Neethling Barnard** (1922–2001), **Robert Koffler Jarvik** (b. 1946)

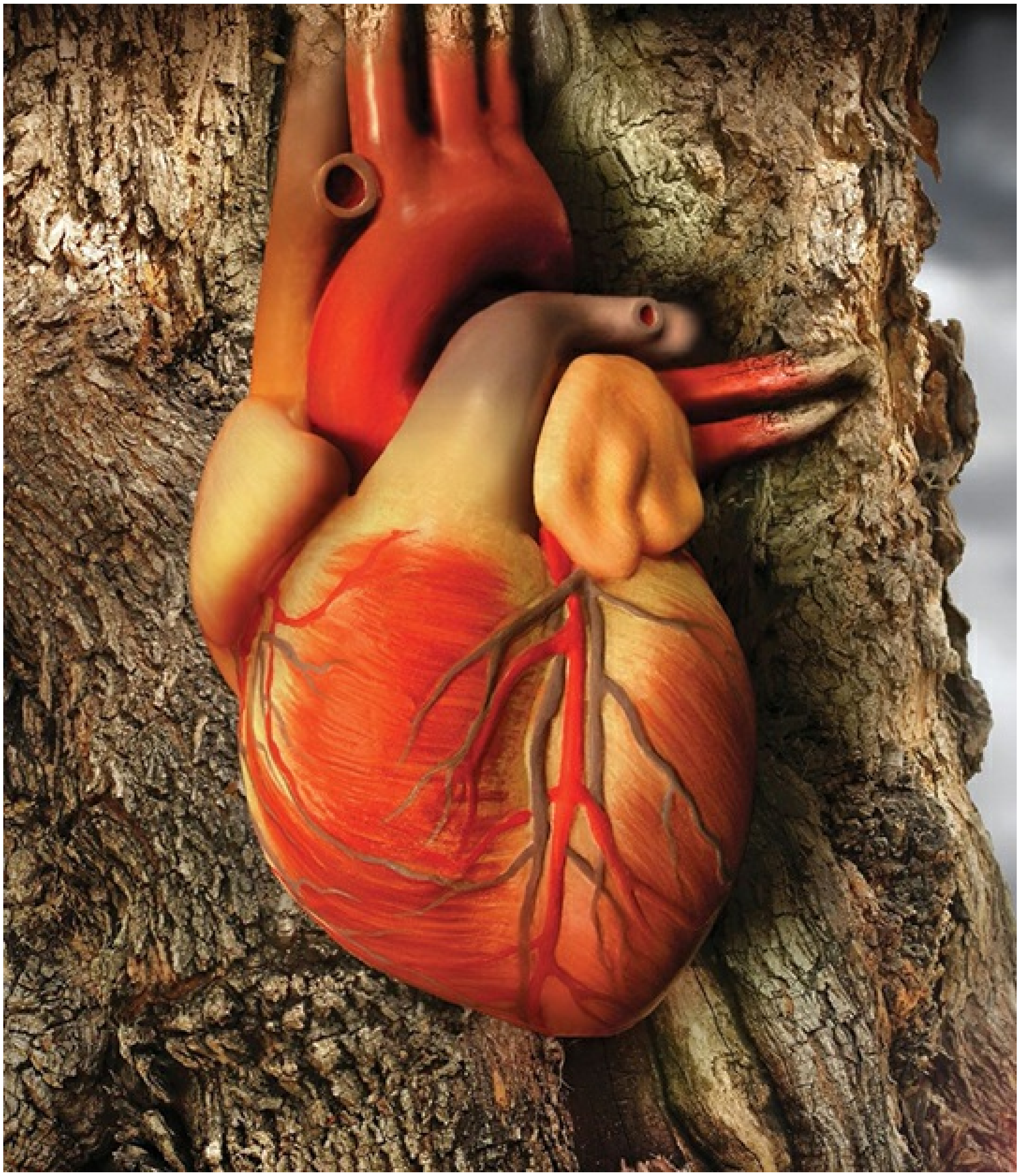
Journalist Laura Fitzpatrick writes, “For much of recorded history, many doctors saw the human heart as the inscrutable, throbbing seat of the soul, an agent too delicate to meddle with.” However, the possibility of heart transplantation—in which the damaged heart of a recipient is replaced with the healthy heart of a deceased donor—became a possibility after the 1953 invention of the heart-lung machine, a device that could temporarily bypass the heart and lungs during surgery and ensure adequate oxygenation of the blood.

In 1964, American surgeon James Hardy performed the first heart transplant when he transplanted the heart of a chimpanzee into the chest of a dying man (no human heart was available). The animal heart beat inside the patient but was too small to keep him alive, and he died after 90 minutes. The world’s first successful human-to-human heart transplant took place in 1967, when South African surgeon Christiaan Barnard removed the heart of a young woman who was killed in a car accident. The recipient was Louis Washkansky, a 54-year-old man who suffered from heart disease. A day later, he was awake and talking. He lived for 18 days and then succumbed to pneumonia caused by the immunosuppressive drugs he was taking to combat rejection of the foreign organ tissue.

Organ transplants became much more successful after the 1972 discovery of **cyclosporine**, a compound derived from fungus that suppressed organ rejection while allowing a significant portion of the body’s immune system to function normally and fight general infection. The prognosis for heart transplant patients was no longer so bleak. For example, although an extreme case, American Tony Huesman survived for 31 years with a transplanted heart. Today, organs that can be transplanted include the heart, kidneys, liver, lungs, pancreas, and intestines. In 1982, American researcher Robert Jarvik implanted the first permanent artificial heart.

SEE ALSO Paré’s “Rational Surgery” (1545), Circulatory system (1628), Blood Transfusion (1829), Artificial Heart (1982).

Artwork titled “Transplants, Resurrection, and Modern Medicine.” A creative artist depicts the human heart growing from a tree, symbolizing the rejuvenation of life provided to recipients of donor hearts—as well as the “miracle” of modern transplant surgery.



1967

Saturn V Rocket • *Marshall Brain*

The Saturn V rocket screams "engineering!" From its ridiculous size to its brute force power to the mission it helped accomplish, it is the most amazing rocket ever created. It holds a number of records, including its 260,000-pound (117,934 kilogram) payload capacity to low Earth orbit.

How could engineers create something this stupendous given the technology available at the time? Most engineers were still using slide rules as this rocket was conceptualized. And how did they create it so quickly? In 1957, the United States had never successfully launched anything into orbit. Yet in 1967 this colossus headed into orbit with ease.

One key was the F-1 engine. Engineers started its development for an Air Force project several years before NASA even existed—a fortunate coincidence. It meant the engine was tested and running smoothly before actually needed. The F-1 is the largest single engine ever created, with a thrust rating of 1.5 million pounds (6.8 meganewtons). Putting five F-1s together on the first stage created 7.6 million pounds of thrust. Which is a good thing because, fully fueled and loaded with payload, the whole rocket weighed about 6.5 million pounds (3,000,000 kg). To launch the rocket, each engine burned almost one million pounds (450,000 kg) of kerosene and liquid oxygen in less than 3 minutes.

Once the first stage fell away, the remainder of the Saturn V was 5 million pounds (2.3 million kg) lighter, and the second and third stages took the payload the rest of the way to orbit burning liquid hydrogen and liquid oxygen.

At the top of the third stage rested an essential component—a ring called the Instrument Unit. At almost 22 feet (7 meters) in diameter, 3 feet (1 meter) high and weighing 2 tons, this ring contained the computers, radios, monitoring equipment, radar, batteries, and other systems to control the three stages during flight and to communicate with ground control. The microprocessor did not exist yet, so the brain here was a custom-made, triple redundant IBM minicomputer.

Engineers created this disposable behemoth to send men to the moon, and then used it to loft Skylab as well. A true engineering wonder.

SEE ALSO Wright Brothers' Airplane (1903), First Humans in Space (1961), First on the Moon (1969).

The Apollo 4 *(Spacecraft 017/Saturn 501) space mission was launched from the Kennedy Space Center, Florida.*

1969

ARPANET • *Marshall Brain*

Donald Davies (1924–2000), **Paul Baran** (1926–2011), **Lawrence Roberts** (b. 1937)

In the 1950s, there were only a few hundred computers in the world, but, by the 1960s, companies were selling thousands of computers. The minicomputer was born in 1965 with the PDP-8, produced by the Digital Equipment Corporation (DEC).

What if you wanted to use a computer? You needed a terminal and a dedicated communication line. To use two computers, you needed two terminals and two lines. People started to consider connecting computers together on networks to allow access to many computers. Electrical engineers created hardware that allowed voice signals to be digitized and then sent as digital data. The T1 line, invented in 1961, could carry 1.5 million bits per second—enough bandwidth for 24 phone calls. Once phone lines could carry digital data, two things could happen: computers could connect together, and different services could be implemented that take advantage of the computers and the connections between them. By organizing all of this, the Internet was born.

The first Internet-like interconnection of computers occurred when four computers connected together in 1969 under the name ARPANET (Advanced Research Projects Agency Network), using concepts and ideas developed by American engineer Paul Baran, Welsh scientist Donald Davies, and Lawrence Roberts of the Lincoln Laboratory. Then this tiny network started growing. By 1984 the number of host computers hit 1,000. By 1987 the number was 10,000.

Two key technologies important to the early Internet were NCP (Network Control Program) and IMPs (Interface Message Processor). Together these technologies created what is known as a packet-switched network between all the computers. When a host computer wanted to send something to another computer, it would break the information down into small data packets and hand the packets of information along with a destination address to its IMP. The IMP, working in conjunction with other IMPs, would deliver the packets to the desired recipient computer. The two computers had no idea how the packets would travel over the network, nor did they care. Once they arrived, packets would be reassembled. NCP would eventually be replaced by TCP/IP (Transmission Control Protocol/Internet Protocol), and IMPs would be replaced by routers. At that point, engineers had created the Internet as we know it today.

SEE ALSO Telephone (1876), ENIAC (1946), Transistor (1947), World Wide Web (1990).

This is a photo of the front panel of the very first Interface Message Processor (IMP). This one was used at the UCLA Boelter 3420 lab to transmit the first message on the Internet.


A
CCN
B
ON
OFF
HALT
INH
W.D.T.
AUTO
RSTRT
MEMORY
PRTCT
IMP STATUS PANEL
INTERFACE
MESSAGE
PROCESSOR
Developed for
the Advanced Research Projects Agency
by Bolt Beranek and Newman Inc.
T1
T2
T3
T4
F
I
A
C
PI
ML
EA
OP
ON
OFF
PFI
PFH
POWER
SENSE
X
B
A
P/Y
OP
M
REGISTER
MASTER
CLEAR
STORE
FETCH
P
P+1
IMP REGISTER PANEL

1969

First on the Moon • *Jim Bell*

Neil A. Armstrong (1930–2012), **Edwin G. “Buzz” Aldrin** (b. 1930), **Michael A. Collins** (b. 1930)

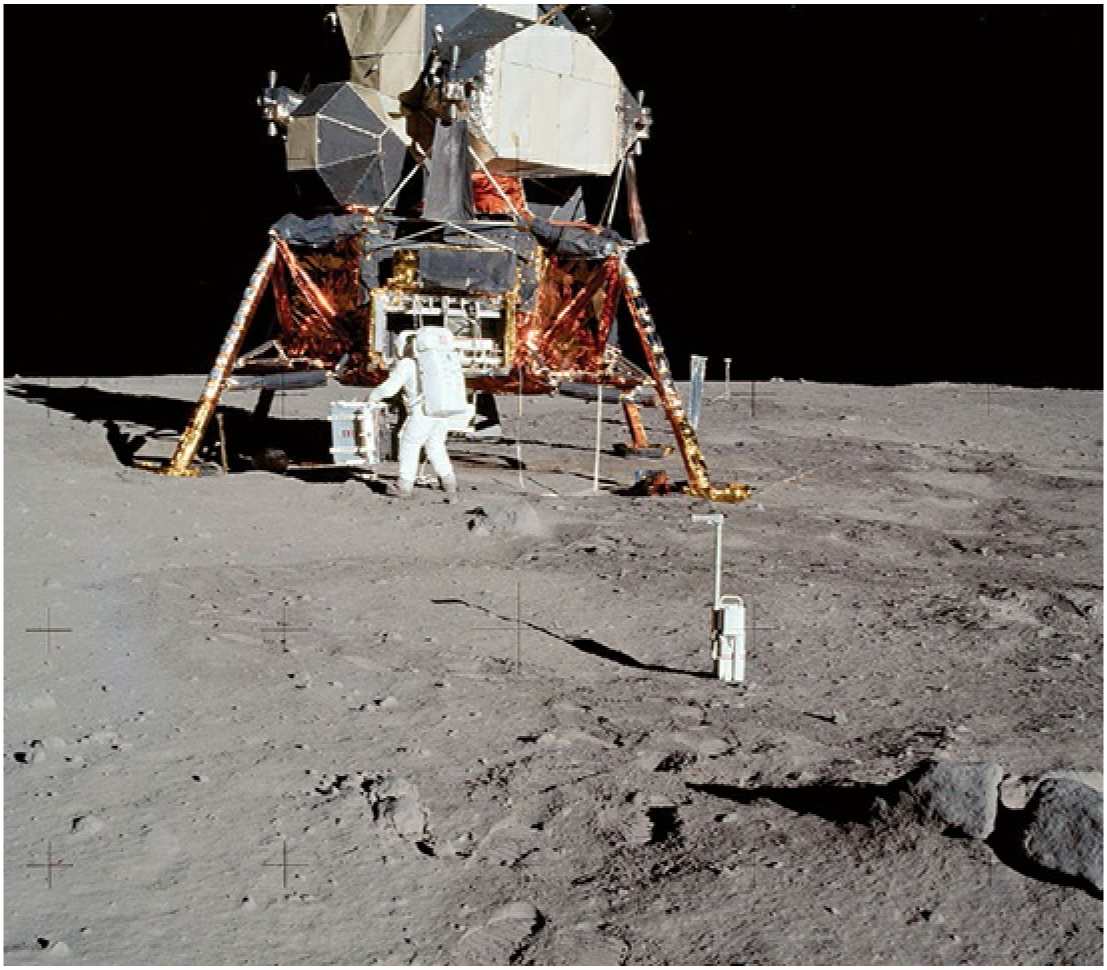
After Yuri Gagarin became the first human in space, the race between the United States and the Soviet Union quickly became focused on the next big milestone: landing astronauts on the Moon and bringing them safely back to the Earth. The Soviet Vostok program was reoriented toward the larger rockets and landing systems needed for a lunar landing and return. In America, the challenge was to beat the Russians and to meet slain president John F. Kennedy’s 1961 goal of doing it “before this decade is out.”

A series of incrementally more advanced US missions were conducted between 1961 and 1969, starting with the Mercury single-astronaut flights, continuing with the Gemini two-person Earth orbital docking and rendezvous flights, and culminating in the three-person Apollo missions to the Moon. *Apollo 8* achieved an important first in 1968 by sending the first humans to orbit the Moon and view the whole Earth and the lunar far side firsthand; the feat was repeated in early 1969 with the flight of *Apollo 10*, a full dress rehearsal of a lunar landing that sent astronauts to within 10 miles (16 kilometers) of the lunar surface before returning home. Meanwhile, the Russians continued to make progress in their own secret lunar cosmonaut program. Several catastrophic unmanned launch failures in 1969 set their program back significantly, however, opening the door for an American victory.

That victory came on July 20, 1969, with the entire world watching as astronauts Neil A. Armstrong and Edwin G. "Buzz" Aldrin became the first humans to land, walk, and work on the moon. Armstrong and Aldrin landed on the ancient volcanic lava flows of the Mare Tranquillitatis (Sea of Tranquillity) impact basin (age dating of the samples showed them to be 3.6–3.9 billion years old), and spent about two and a half hours collecting samples and exploring the terrain. After less than a day, they took off and rejoined command module pilot Michael A. Collins back in lunar orbit for the three-day trip home—as world heroes.

SEE ALSO Wright Brothers' Airplane (1903), First Humans in Space (1961), Saturn V Rocket (1967).

ABOVE: *Buzz Aldrin's bootprint in the fine, powdery lunar soil.* BELOW: Apollo 11 *astronaut Aldrin unloads scientific equipment from the lunar module* Eagle *at the landing site in Mare Tranquillitatis (photo taken by Neil Armstrong).*



1972

Genetic Engineering • *Marshall Brain*

Paul Berg (b. 1926)

When we think about engineering, we generally think about creating a new object: a new building, a new device, a new mechanism. Genetic engineering is a different type of endeavor. Here we are taking an existing system that is quite complicated and that we do not completely understand—a genome—and we are tinkering with it. Genetic engineers add new genes to a genome to create new behaviors.

The predecessor to genetic engineering is selective breeding. Breeders select desired traits. With selective breeding we have created all the various breeds of dogs.

But genetic engineering, which appeared in 1972, when American biochemist Paul Berg created the first recombinant DNA molecules, is something altogether different: Engineers are injecting new genes into genomes in ways nature could never accomplish. For example, Berg combined two viruses. Other more recent applications have included a jellyfish gene that produces a green fluorescent protein added to a fish or a mouse, creating fluorescent mice. A gene that makes a plant immune to an herbicide gets added to soybean plants so that the herbicide won't kill them.

In one of the most bizarre examples, genetic engineers took genes for producing spider silk and added them to goats. The proteins of spider silk appear in the milk of a female goat. The goal was to extract the proteins to create super strong, highly elastic materials.

There are different ways to inject the genes of one organism into another, and the gene gun is one popular tool. The technique is so simple, it is amazing that it works. The gene to be injected is added, in liquid form, to tiny particles of tungsten or gold. The particles are shot out of a gun, shotgun style, at a petri dish full of target cells. Some of the cells get punctured, but not killed, and they pick up the new gene.

By injecting genes from one organism into another, genetic engineers are able to create new organisms. One of the most beneficial examples is human insulin produced by *E. coli* bacteria. Developed in the 1980s, genetically engineered insulin is used by millions of people today.

SEE ALSO Mendel's Genetics (1865), Chromosomal Theory of Inheritance (1902), HeLa cells (1951), DNA Structure (1953), Epigenetics (1983).

GloFish,® the first genetically modified organism (GMO) designed as a pet (a fluorescent fish), was first sold in the United States in December 2003.

1975

Feigenbaum Constant • *Clifford A. Pickover*

Mitchell Jay Feigenbaum (b. 1944)

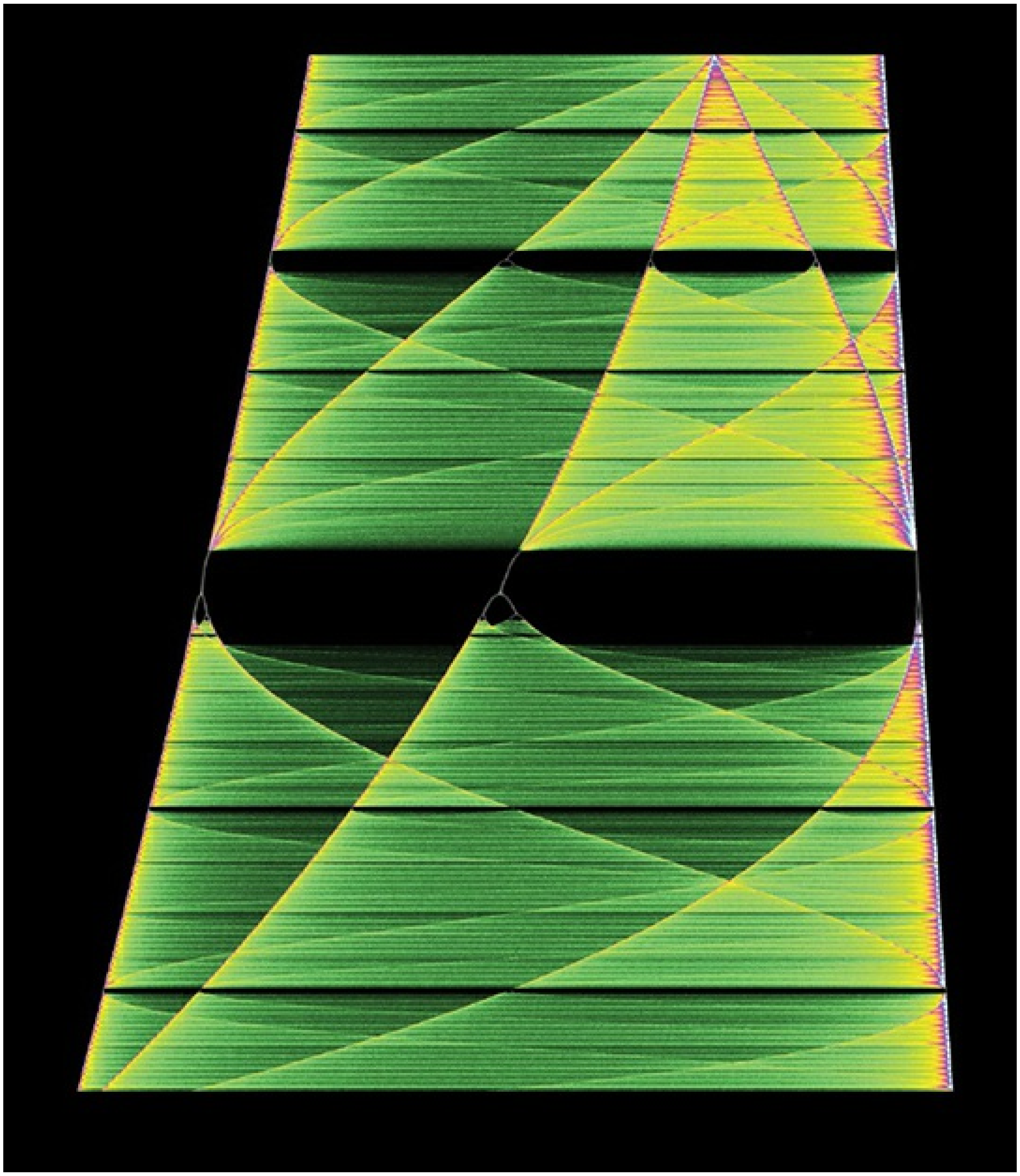
Simple formulas can produce amazingly diverse and chaotic behaviors while characterizing phenomena ranging from the rise and fall of animal populations to the behavior of certain electronic circuits. One formula of special interest is the logistic map, which models population growth and was popularized by biologist Robert May in 1976 and based on the earlier work of Belgian mathematician Pierre François Verhulst (1804–1849), who researched models of population changes. The formula may be written as $x_{n+1} = rx_n(1 - x_n)$. Here, x represents the population at time n. The variable x is defined relative to the maximum population size of the ecosystem and therefore has values between 0 and 1. Depending on the value of r, which controls the rate of growth and starvation, the population may undergo many behaviors. For example, as r is increased, the population may converge to a single value, or bifurcate so that it oscillates between two values, then oscillates between four values, then eight values, and finally becomes chaotic such that slight changes in the initial population yield very different, unpredictable outcomes.

The ratio of the distances between two successive bifurcation intervals approaches the Feigenbaum constant, 4.6692016091. . ., a number discovered by American mathe-matical physicist Mitchell Feigenbaum in 1975. Interestingly, although Feigenbaum initially considered this constant for a map similar to the logistic map, he also showed that it applied to all one-dimensional maps of this kind. This means that multitudes of chaotic systems will bifurcate at the same rate, and thus his constant can be used to predict when chaos will be exhibited in systems. This kind of bifurcation behavior has been discovered in many physical systems before they enter the chaotic regime.

Feigenbaum quickly realized that his "universal constant" was important, remarking that "I called my parents that evening and told them that I had discovered something truly remarkable, that, when I had understood it, would make me a famous man."

SEE ALSO Cellular Automata (1952), Chaos and the Butterfly Effect (1963), Fractals (1975).

Bifurcation diagram (rotated clockwise by 90º), by Steven Whitney. This figure reveals the incredibly rich behavior of a simple formula as a parameter r is varied. Bifurcation "pitchforks" can be seen as small, thin, light branching curves amidst the chaos.



1975

Fractals • *Clifford A. Pickover*

Benoît B. Mandelbrot (1924–2010)

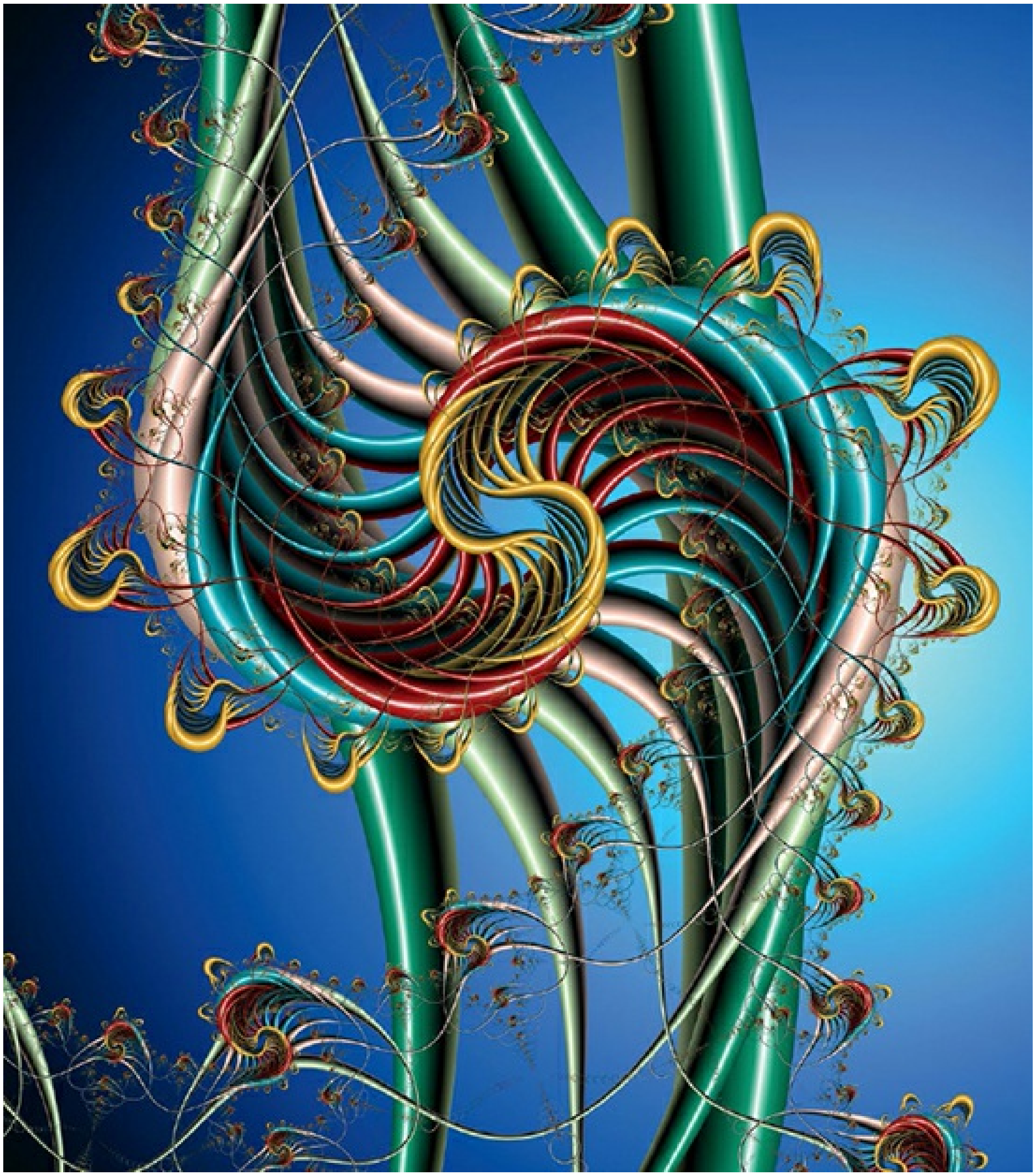
Today, computer-generated fractal patterns are everywhere. From squiggly designs on computer art posters to illustrations in the most serious of physics journals, interest continues to grow among scientists and, rather surprisingly, artists and designers. The word *fractal* was coined in 1975 by mathematician Benoît Mandelbrot to describe an intricate-looking set of curves, many of which were never seen before the advent of computers with their ability to quickly perform massive calculations. Fractals often exhibit self-similarity, which suggests that various exact or inexact copies of an object can be found in the original object at smaller size scales. The detail continues for many magnifications—like an endless nesting of Russian dolls within dolls. Some of these shapes exist only in abstract geometric space, but others can be used as models for complex natural objects such as coastlines and blood vessel branching. The dazzling computer-generated images can be intoxicating, motivating students' interest in math more than any other mathematical discovery in the last century.

Physicists are interested in fractals because they can sometimes describe the chaotic behavior of real-world phenomena such as planetary motion, fluid flow, the diffusion of drugs, the behavior of inter-industry relationships, and the vibration of airplane wings. (Chaotic behavior often produces fractal patterns.) Traditionally, when physicists or mathematicians saw complicated results, they often looked for complicated causes. In contrast, many fractal shapes reveal the fantastically complicated behavior of the simplest formulas.

Early explorers of fractal objects include Karl Weierstrass, who in 1872 considered functions that were everywhere continuous but nowhere differentiable, and Helge von Koch, who in 1904 discussed geometric shapes such as the Koch snowflake. In the nineteenth and early twentieth centuries, several mathematicians explored fractals in the complex plane; however, they could not fully appreciate or visualize these objects without the aid of the computer.

SEE ALSO Descartes' *La Géométrie* (1637), Pascal's Triangle (1654), Chaos and the Butterfly Effect (1963).

Fractal structure by Jos Leys. Fractals often exhibit self-similarity, which suggests that various structural themes are repeated at different size scales.



1977

Public-Key Cryptography • *Clifford A. Pickover*

Ronald Lorin Rivest (b. 1947), **Adi Shamir** (b. 1952), **Leonard Max Adleman** (b. 1945), **Bailey Whitfield Diffie** (b. 1944), **Martin Edward Hellman** (b. 1945), **Ralph C. Merkle** (b. 1952)

Throughout history, cryptologists have sought to invent a means for sending secret messages without the use of cumbersome code books that contained encryption and decryption keys that could easily fall into enemy hands. For example, the Germans, between 1914 and 1918, lost four code books that were recovered by British intelligence services. The British code-breaking unit, known as Room Forty, deciphered German communications, giving Allied forces a crucial strategic advantage in World War I.

In order to solve the key management problem, in 1976, Whitfield Diffie, Martin Hellman, and Ralph Merkle at Stanford University, California, worked on public-key cryptography, a mathematical method for distributing coded messages through the use of a pair of cryptographic keys: a public key and a private key. The private key is kept secret, while, remarkably, the public key may be widely distributed without any loss of security. The keys are related mathematically, but the private key cannot be derived from the public key by any practical means. A message encrypted with the public key can be decrypted only with the corresponding private key.

To better understand public-key encryption, imagine a mail slot in the front door to a home. Anyone on the street can stuff something into the mail slot;

the public key is akin to the house address. However, only the person who possesses the key to the house door can retrieve the mail and read it.

In 1977, MIT scientists Ronald Rivest, Adi Shamir, and Leonard Adleman suggested that large prime numbers could be used to guard the messages. Multiplication of two large prime numbers is easy for a computer, but the reverse process of finding the two original prime numbers given their product can be very difficult. It should be noted that computer scientists had also developed public-key encryption for the British intelligence at an earlier date; however, this work was kept secret for reasons of national security.

SEE ALSO Sieve of Eratosthenes (c. 240 BCE) Proof of the Prime Number Theorem (1896), ENIAC (1946).

Enigma machine, used to code and decode messages before the age of modern cryptography. The Nazis used Enigma-produced ciphers, which had several weaknesses, such as the fact that the messages could be decoded if a code book was captured.


Q W E R T Z U I O
A S D F G H J K
P Y X C V B N M L

1978

Theory of Mind • *Wade E. Pickren*

David Premack (1925–2015)

The ability to imagine what other people feel or think and to respond accordingly is one of the most important accomplishments of social development. Modern developmental science has been intensively studying this ability in infants, children, chimpanzees, and even rodents for about thirty years.

Developmental psychologists call this ability theory of mind (ToM). It is a principle that can be found in several of the world's major religions, but in psychology, David Premack and Guy Woodruff offered one of the first full expressions of ToM in 1978. Formally, theory of mind refers to children's understanding that others also have thoughts, beliefs, objectives, and emotions. Without ToM, the child would not be able to pick up on the social cues or intentions of others, as is often the case when a child suffers from autism.

Theory of mind is a developmental process that, in normally developing children, is usually fully in place by about age four or five. Scientists have found that the critical precursors of ToM occur as early as seven to nine months as the infant learns that the attention of others can be directed by simple tasks like pointing or reaching. By the end of the first year, infants are beginning to understand that people have intentions. But it is not until about age four or five that children truly understand that there is a link between how others feel or think and what they do.

Neuroscientists using brain-imaging techniques have shown that this is exactly the age when the prefrontal cortex of the brain is rapidly maturing. For children with autism, this is not the case, although there are interventions that can help improve the brain’s responses in children with autism.

Theory of mind is crucially important for displaying empathy and caring for others. It makes it possible for us to be socially competent. Research on ToM has greatly facilitated our understanding of children’s social development, with implications for emotional and cognitive development. It is also a principle that facilitated the reception of mirror neurons.

SEE ALSO *The Principles of Psychology* (1890), Psychoanalysis (1899), Classical Conditioning (1903), Placebo Effect (1955), Cognitive Behavior Therapy (1963).

By age four or five, normal children learn that a person’s actions link to what they feel and think—a crucial step in the development of empathy and social competence.

1979

Gravitational Lensing • *Jim Bell*

One of the fundamental features of physicist Albert Einstein's early-twentieth-century theory of general relativity is that space and time are curved near extremely massive objects. The curvature of space-time led Einstein and others to predict that light from distant objects would be bent by the gravitational field of massive foreground objects. The prediction was verified in 1919 by the British astrophysicist Arthur Stanley Eddington, who noticed that stars observed near the Sun during a solar eclipse were slightly out of position. Einstein continued to study this effect in the 1930s, and he and others, including the Swiss-American astronomer Fritz Zwicky, speculated that more massive objects, such as galaxies and clusters of galaxies, could bend and amplify light from distant objects almost as a lens bends and magnifies normal light.

It took many decades for astronomers to find observational evidence of such gravitational lensing, however. The first example was discovered in 1979 by astronomers at the Kitt Peak National Observatory in Arizona, who found an example of what appeared to be twin quasars—two active galactic nuclei very close to each other in the sky. The two quasars were shown to actually be a single object whose light was bent and split into two parts by the strong gravitational field of a foreground galaxy.

Since then, many more examples of gravitational lensing have been found, and the effect seems to occur in three ways: strong lensing is when distinct multiple or partial (usually arc-like) images are formed; weak lensing has been detected by observing small and subtle shifts in star or galaxy positions over large regions; and microlensing events have been detected when random distant stars (or even planets) have their brightness temporarily amplified by the gravitational lensing effect of a large foreground mass, such as another star or galaxy.

Gravitational lenses were initially discovered and studied as accidental, serendipitous events. Recently, however, a number of astronomical surveys have been conducted to intentionally search for gravitational lensing events, in order to obtain unique measurements of the properties of distant galaxies that would not be visible without the amplification from the lens, as well as the properties (such as mass) of the lensing galaxies and clusters themselves.

SEE ALSO Newton's Laws of Motion and Gravitation (1687), Black Holes (1783), General Theory of Relativity (1915).

The thin arcs seen here are gravitationally lensed galaxies in the galactic cluster Abell 2218, photographed by the Hubble Space Telescope in 1999. These so-called Einstein rings are the smeared-out light from distant galaxies being bent by a massive foreground galaxy.

1980

Cosmic Inflation • *Clifford A. Pickover*

Alan Harvey Guth (b. 1947)

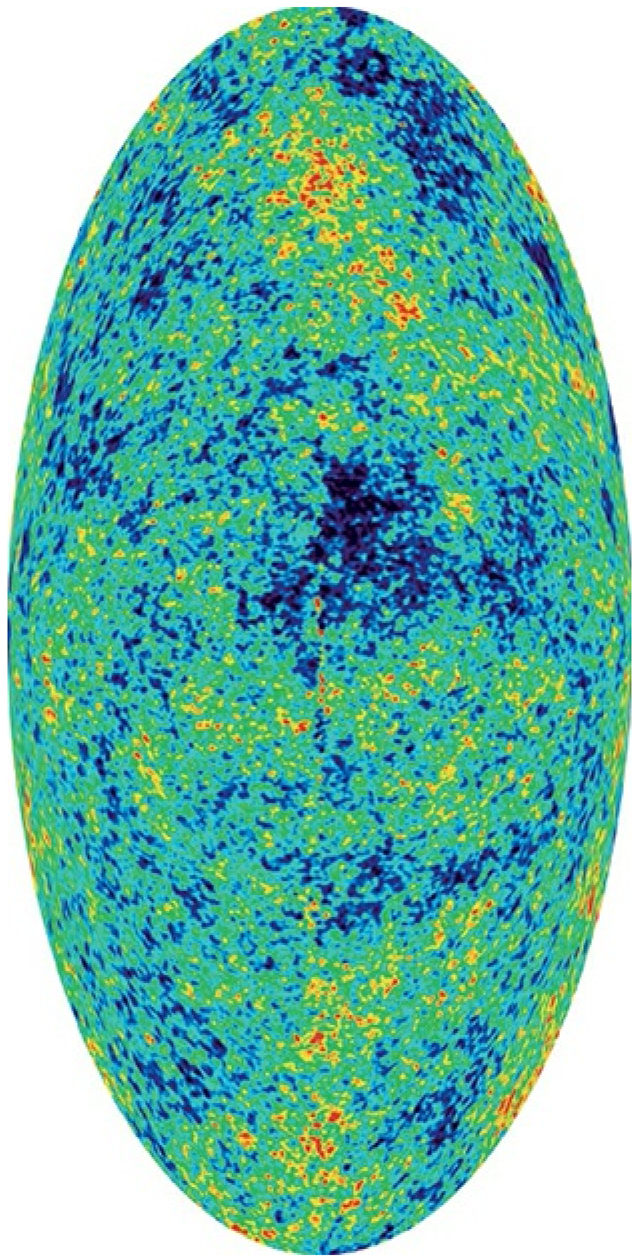
The Big Bang theory states that our universe was in an extremely dense and hot state 13.7 billion years ago, and space has been expanding ever since. However, the theory is incomplete because it does not explain several observed features in the universe. In 1980, physicist Alan Guth proposed that 10^{-35} seconds (a 100 billion trillion trillionths of a second) after the Big Bang, the universe expanded (or inflated) in a mere 10^{-32} seconds from a size smaller than a proton to the size of a grapefruit—an increase in size of 50 orders of magnitude. Today, the observed temperature of the background radiation of the universe seems relatively constant even though the distant parts of our visible universe are so far apart that they do not appear to have been connected, unless we invoke inflation that explains how these regions were originally in close proximity (and had reached the same temperature) and then separated faster than the speed of light.

Additionally, inflation explains why the universe appears to be, on the whole, quite “flat”—in essence why parallel light rays remain parallel, except for deviations near bodies with high gravitation. Any curvature in the early universe would have been smoothed away, like stretching the surface of a ball until it is flat. Inflation ended 10^{-30} seconds after the Big Bang, allowing the universe to continue its expansion at a more leisurely rate.

Quantum fluctuations in the microscopic inflationary realm, magnified to cosmic size, become the seeds for larger structures in the universe. Science-journalist George Musser writes, “The process of inflation never ceases to amaze cosmologists. It implies that giant bodies such as galaxies originated in teensy-weensy random fluctuations. Telescopes become microscopes, letting physicists see down to the roots of nature by looking up into the heavens." Alan Guth writes that inflationary theory allows us to "consider such fascinating questions as whether other big bangs are continuing to happen far away, and whether it is possible in principle for a super-advanced civilization to recreate the big bang."

SEE ALSO Cosmic Microwave Background (1965), Hubble's Law of Cosmic Expansion (1929), Parallel Universes (1956), Dark Energy (1998).

A map produced by the Wilkinson Microwave Anisotropy Probe (WMAP) showing a relatively uniform distribution of cosmic background radiation, produced by an early universe more than 13 billion years ago. Inflation theory suggests that the irregularities seen here are the seeds that became galaxies.



1981

Quantum Computers • *Clifford A. Pickover*

Richard Phillips Feynman (1918–1988), **David Elieser Deutsch** (b. 1953)

One of the first scientists to consider the possibility of a quantum computer was physicist Richard Feynman who, in 1981, wondered just how small computers could become. He knew that when computers finally reached the size of sets of atoms, the computer would be making use of the strange laws of quantum mechanics. Physicist David Deutsch in 1985 envisioned how such a computer would actually work, and he realized that calculations that took virtually an infinite time on a traditional computer could be performed quickly on a quantum computer.

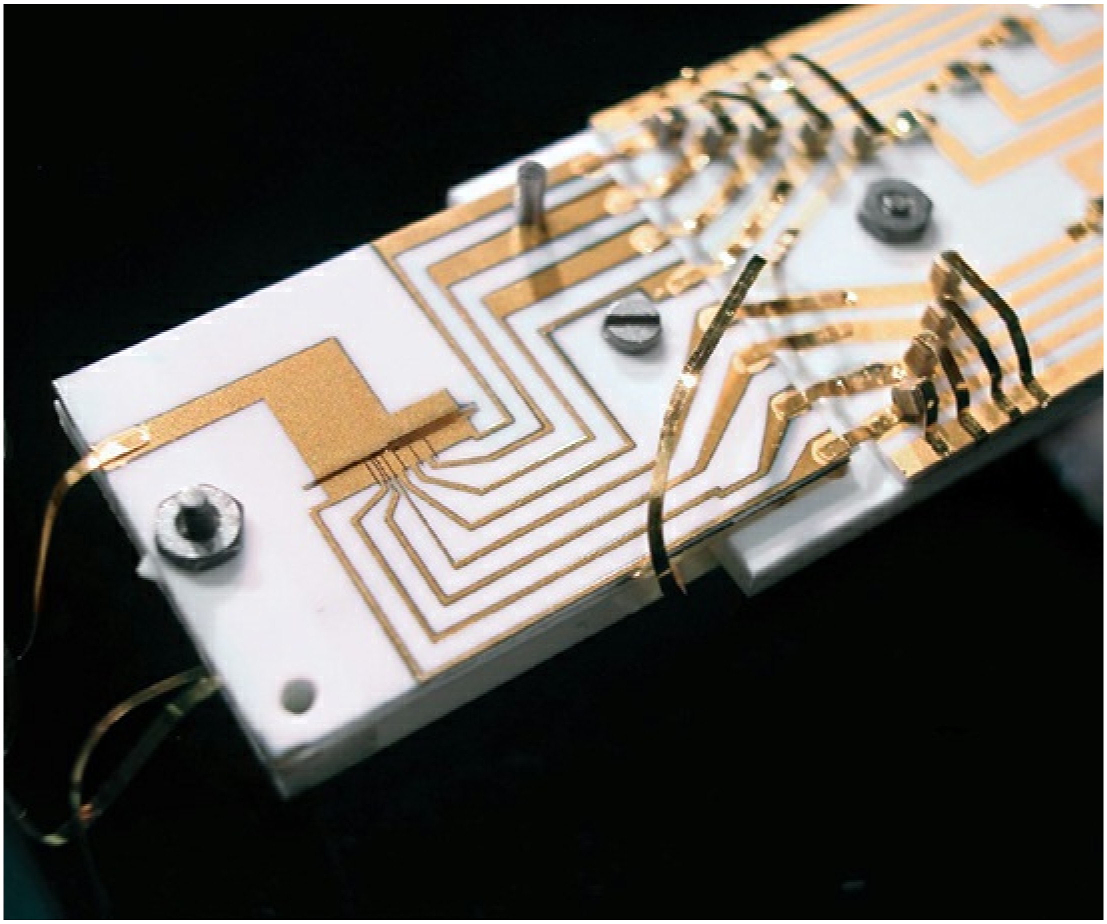
Instead of using the usual binary code, which represents information as either a 0 or 1, a quantum computer uses qubits, which essentially are simultaneously both 0 and 1. Qubits are formed by the quantum states of particles, for example, the spin state of individual electrons. This superposition of states allows a quantum computer to effectively test every possible combination of qubits at the same time. A thousand-qubit system could test $2^{1,000}$ potential solutions in the blink of an eye, thus vastly outperforming a conventional computer. To get a sense for the magnitude of $2^{1,000}$ (which is approximately 10^{301}), note that there are only about 10^{80} atoms in the visible universe.

Physicists Michael Nielsen and Isaac Chuang write, “It is tempting to dismiss quantum computation as yet another technological fad in the evolution of the computer that will pass in time. . . . This is a mistake, since quantum computation is an *abstract* paradigm for information processing that may have many *different* implementations in technology."

Of course, many challenges still exist for creating a practical quantum computer. The slightest interaction or impurity from the surroundings of the computer could disrupt its operation. "These quantum engineers . . . will have to get information into the system in the first place," writes author Brian Clegg, "then trigger the operation of the computer, and, finally, get the result out. None of these stages is trivial. . . . It's as if you were trying to do a complex jigsaw puzzle in the dark with your hands tied behind your back."

SEE ALSO Complementarity Principle (1927), EPR Paradox (1935), Parallel Universes (1956), Integrated Circuit (1958).

In 2009, physicists at the National Institute of Standards and Technology demonstrated reliable quantum information processing in the ion trap at the left center of this photograph. The ions are trapped inside the dark slit. By altering the voltages applied to each of the gold electrodes, scientists can move the ions between the six zones of the trap.



1982

Artificial Heart • *Marshall Brain*

Robert Jarvik (b. 1946)

In healthy people, the heart beats without pause for an entire lifetime, pumping 5 million gallons (19 million liters) of blood or more during 70 or 80 years of operation. But when something goes wrong and a heart needs to be replaced, the scarcity of natural replacement hearts creates a big problem. Thus engineers set about trying to design and build artificial mechanical hearts. However, nature's pump is very difficult to duplicate.

There were four problems that doctors and engineers had to solve to make an artificial heart work: 1) Finding materials with the right chemistry and properties so that they did not cause an immune reaction or internal clotting in the patient, 2) Finding a pumping mechanism that did not damage blood cells, 3) Finding a way to power the device, 4) Making the device small enough to fit inside the chest cavity.

The Jarvik-7 heart, designed by American scientist Robert Jarvik and his team in 1982, was the first device to meet these requirements reliably. It features two ventricles like a natural heart. Its materials avoided rejection and were smooth and seamless enough to prevent clotting. The pumping mechanism used a balloon-like diaphragm in each ventricle that, as they inflated, pushed blood through the one-way valve without damaging blood cells. The only compromise was the air compressor, which remained outside the body and transmitted air pulses to the heart with hoses running through the abdominal wall. The basic design was successful and has since been improved as the Syncardia heart, used in over 1,000 patients. One patient lived almost four years with the heart before receiving a transplant. The Abiocor heart uses a different approach that allows batteries and an inductive charging system to be implanted completely inside the body. It also has a diaphragm arrangement but fluid flow rather than air fills the diaphragms. The fluid flow comes from a small electric motor embedded inside the heart.

Two different engineering approaches: One goes for complete embedding. But if something goes wrong, it probably means death. In the other, much of the system is outside the body for easy access and repair, but tubes pass into the body from outside.

SEE ALSO Circulatory System (1628), Blood Transfusion (1829), Heart Transplant (1967).

The SynCardia temporary Total Artificial Heart (TAH-t), pictured, is the first and only temporary TAH approved by the FDA (U.S. Food and Drug Administration) and Health Canada. It is also approved for use in Europe through the CE (Conformité Européenne) mark.

1983

Epigenetics • *Clifford A. Pickover*

Bert Vogelstein (b. 1949)

Just as a pianist interprets the notes in a musical score, controlling the volume and tempo, epigenetics affects the interpretation of DNA genetic sequences in cells. Epigenetics usually refers to the study of heritable traits that do not involve changes to the underlying DNA sequences of cells.

One way in which DNA expression can be controlled is by the addition of a methyl group (a carbon atom with three attached hydrogen atoms) to one of the DNA bases, making this “marked” area of the DNA less active and potentially suppressing the production of a particular protein. Gene expression can also be modified by the histone proteins that bind to the DNA molecule.

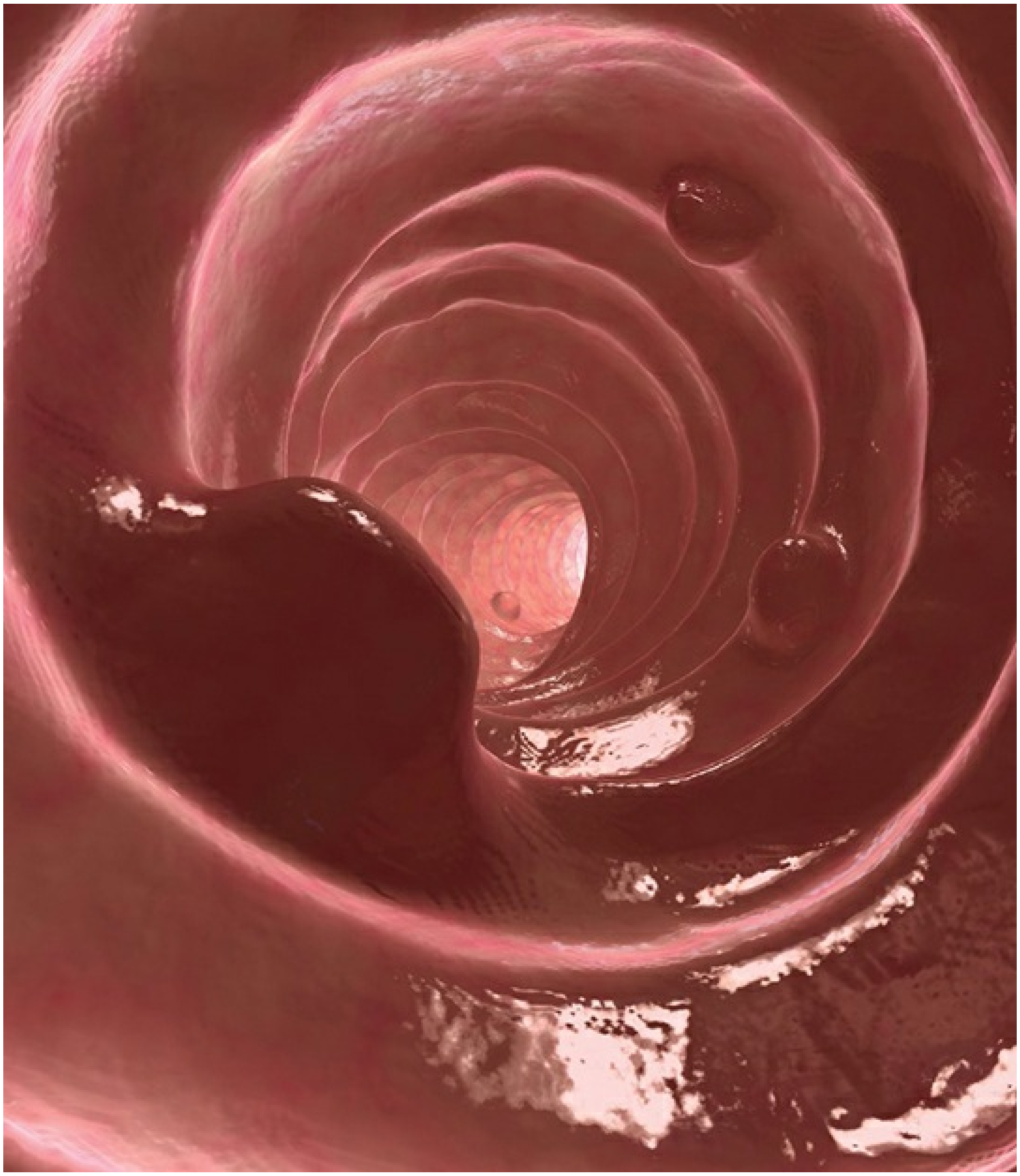
In the 1980s, Swedish researcher Lars Olov Bygren discovered that boys in Norrbotten, Sweden, who had gone from normal eating to vast overeating in a single season produced sons and grandsons who lived much shorter lives. One hypothesis is that inherited epigenetic factors played a role. Other studies suggest that environmental factors such as stress, diet, smoking, and prenatal nutrition make imprints on our genes that are passed through generations. According to this argument, the air your grandparents breathed and the food they ate can affect your health decades later.

In 1983, American medical researchers Bert Vogelstein and Andrew P. Feinberg documented the first example of a human disease with an epigenetic mechanism. In particular, they observed widespread loss of DNA methylation in colorectal **cancers**. Because methylated genes are typically turned off, this loss of methylation can lead to abnormal *activation* of genes in cancer. Additionally, too much methylation can undo the work of protective tumor-suppressor genes. Drugs are currently being developed that affect epigenetic markers that silence bad genes and activate good ones.

The general concept of epigenetics is not new. After all, a brain cell and liver cell have the same DNA sequence, but different genes are activated through epigenetics. Epigenetics may explain why one identical twin develops asthma or bipolar disorder while the other remains healthy.

SEE ALSO Causes of Cancer (1761), Chromosomal Theory of Inheritance (1902), DNA Structure (1953), Human Genome Project (2003), Gene Therapy (2016).

Loss of DNA methylation (marking) can occur in colorectal cancer, such as in the polyps shown here. Because methylated genes are typically turned off, this loss of methylation can lead to abnormal activation of genes involved in cancer.



1983

Polymerase Chain Reaction • *Clifford A. Pickover*

Kary Banks Mullis (b. 1944)

In 1983, while driving along a California highway, biochemist Kary Mullis had an idea for how to copy a microscopic strand of genetic material billions of times within hours—a process that has since had countless applications in medicine. Although his idea for the polymerase chain reaction (PCR) turned into a billion-dollar industry, he received only a $10,000 bonus from his employer. Perhaps his Nobel Prize ten years later can be viewed as a sufficiently awesome consolation prize.

Scientists usually require a significant amount of a particular DNA genetic sequence in order to study it. The groundbreaking PCR technique, however, can start with as little as a single molecule of the DNA in a solution, with the aid of Taq polymerase, an enzyme that copies DNA and that stays intact when the solution is heated. (Taq polymerase was originally isolated from a bacterium that thrived in a hot spring of America's Yellowstone National Park.) Also added to the brew are primers—short segments of DNA that bind to the sample DNA at a position before and after the sequence under study. During repeated cycles of heating and cooling, the polymerase begins to rapidly make more and more copies of the sample DNA between the primers. The thermal cycling allows the DNA strands to repeatedly pull apart and come together as needed for the copying process. PCR can be used for detecting food-borne pathogens, diagnosing genetic diseases, assessing the level of HIV viruses in AIDS patients, determining paternity of babies, finding criminals based on traces of DNA left at a crime scene, and studying

DNA in fossils. PCR was important in advancing the Human Genome Project.

Medical journalist Tabitha Powlege writes, “PCR is doing for genetic material what the invention of the printing press did for written material—making copying easy, inexpensive, and accessible.” The *New York Times* referred to Mullis’s invention as “dividing biology into the two epochs of before PCR and after PCR.”

SEE ALSO Chromosomal Theory of Inheritance (1902), DNA Structure (1953).

PCR has been used to amplify DNA from 14,000-year-old fossil bones of saber-toothed cats preserved in asphalt. Such studies help scientists compare these extinct animals to various living cat species in order to better understand cat evolution.

1984

Telomerase • *Clifford A. Pickover*

Elizabeth Helen Blackburn (b. 1948), **Carolyn Widney "Carol" Greider** (b. 1961)

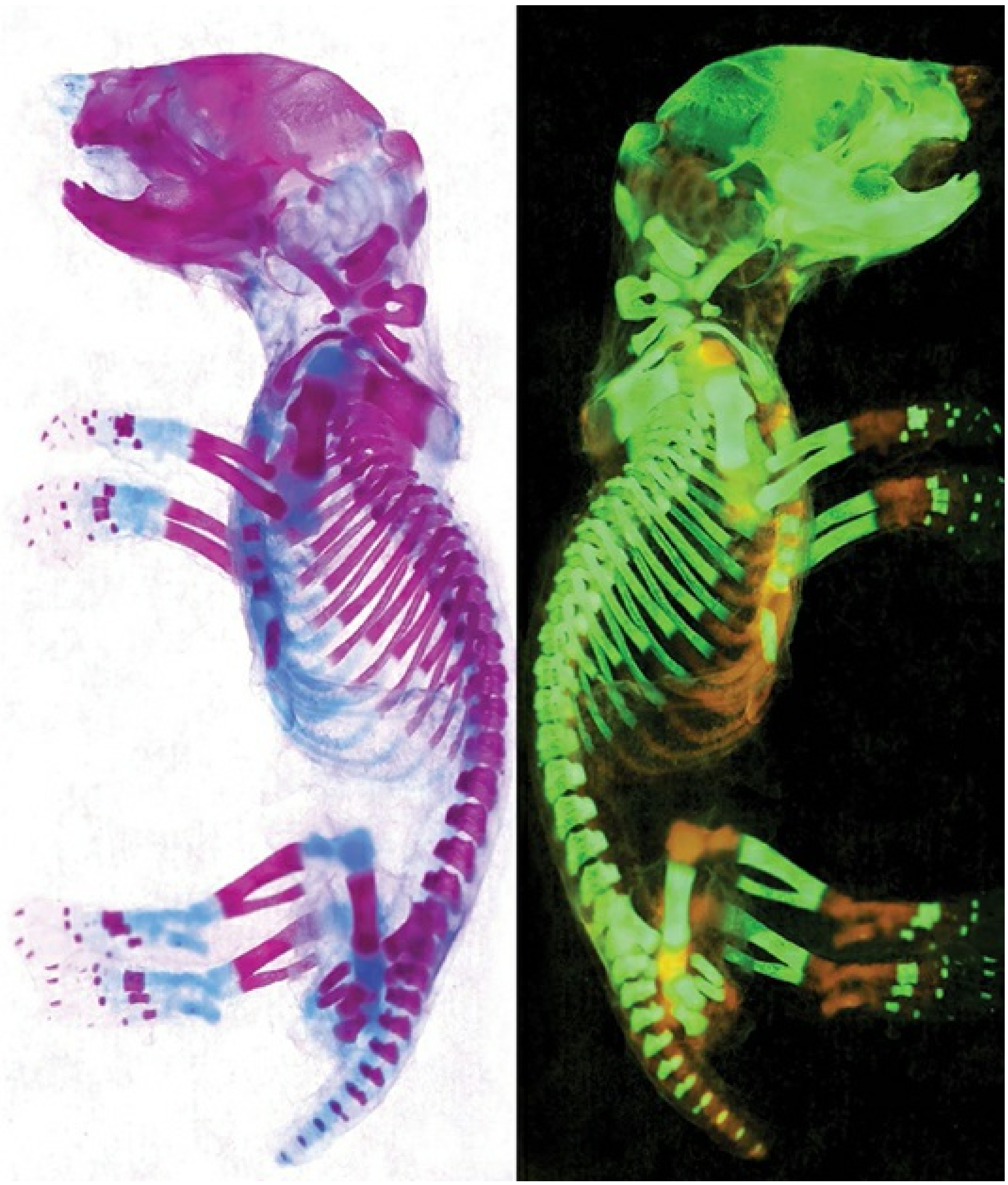
The chromosomes in our cells are each made of a long coiled DNA molecule wrapped around a protein scaffold. The ends of each chromosome have a special protective cap called a telomere that contains a sequence of bases represented as TTAGGG. Although the enzyme that copies DNA for cell division cannot quite copy to the very end of each chromosome, the telomere compensates for this potential flaw because the endpieces are simply TTAGGG, potentially repeated more than 1,000 times. However, with each cell division, a portion of the telomere is lost through this erosion process, and when the telomere becomes too short, the chromosome can no longer be replicated in these "old" cells. Many body cells enter a state of senescence (inability to divide) after about 50 cell divisions in a culture dish.

In 1984, while studying the microscopic protozoan *Tetrahymena*, biologists Carol Greider and Elizabeth Blackburn discovered telomerase, an enzyme with an RNA component that can counteract the chromosome erosion and elongate the telomeres by returning TTAGGG to the chromosome ends. Telomerase activity is very low in most somatic (nonreproductive) cells, but it is active in fetal cells, adult germ cells (which produce **sperm** and egg), immune system cells, and tumor cells—all of which may divide regularly. These discoveries suggest a connection between telomerase activity and both aging and **cancer**. Thus, various experiments are underway to test the idea of triggering telomerase activation or inactivation in order to either increase lifespan (by making cells immortal) or inhibit cancers (by changing immortal, continuously dividing cells to mortal ones). Several premature-aging diseases in humans are associated with short telomeres, and telomerase activation has been discovered in a majority of human tumors. Note that because the single-celled, freshwater *Tetrahymena* organism has active telomerase, it can divide indefinitely—and is, essentially, immortal.

Greider and Blackburn write, "In the early 1980s, scientists would not have set out to identify potential anticancer therapies by studying chromosome maintenance in *Tetrahymena*. . . . In studies of nature, one can never predict when and where fundamental processes will be uncovered."

SEE ALSO Causes of Cancer (1761), Cell Division (1855), Chromosomal Theory of Inheritance (1902), HeLa cells (1951), DNA Structure (1953).

Mice that are engineered to lack telomerase become prematurely old but return to health when the enzyme is replaced. Researchers can use certain stains to study development and degeneration of bone and cartilage in mice.



1984

Theory of Everything • *Clifford A. Pickover*

Michael Boris Green (b. 1946), **John Henry Schwarz** (b. 1941)

"My ambition is to live to see all of physics reduced to a formula so elegant and simple that it will fit easily on the front of a T-shirt," wrote physicist Leon Lederman. "For the first time in the history of physics," writes physicist Brian Greene, we "have a framework with the capacity to explain every fundamental feature upon which the universe is constructed [and that may] explain the properties of the fundamental particles and the properties of the forces by which they interact and influence one another."

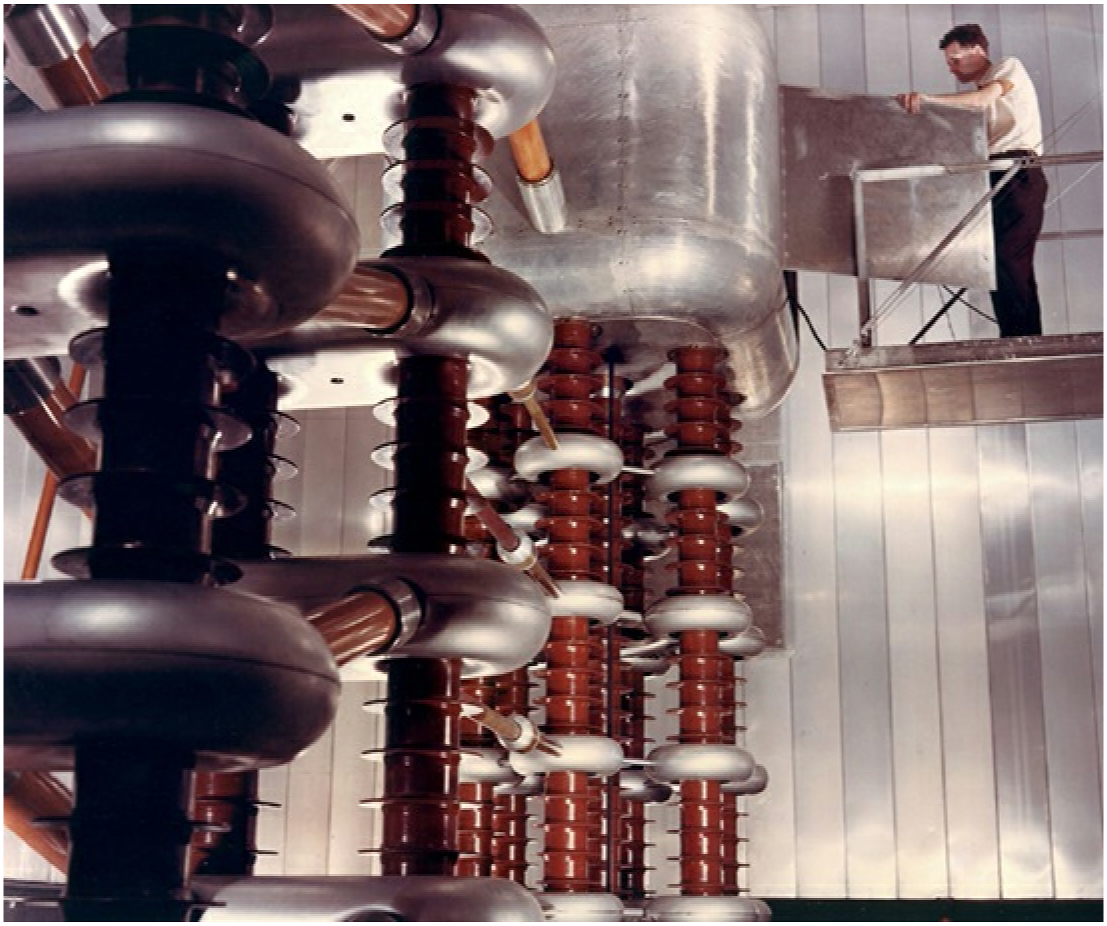
The theory of everything (TOE) would conceptually unite the four fundamental forces of nature, which are, in decreasing order of strengths: 1) the *strong nuclear force*—which holds the nucleus of the atom together, binds quarks into elementary particles, and makes the stars shine, 2) the *electromagnetic force*—between electric charges and between magnets, 3) the *weak nuclear force*—which governs the radioactive decay of elements, and 4) the *gravitational force*—which holds the Earth to the Sun. Around 1967, physicists showed how electromagnetism and the weak forces could be unified as the *electroweak* force.

Although not without controversy, one candidate for a possible TOE is M-theory, which postulates that the universe has ten dimensions of space and one of time. The notion of extra dimensions also may help resolve the *hierarchy problem* concerning why gravity is so much weaker than the other forces. One solution is that gravity leaks away into dimensions beyond our ordinary three spatial dimensions. If humanity did find the TOE, summarizing the four forces in a short equation, this would help physicists determine if time machines are possible and what happens at the center of black holes, and, as astrophysicist Stephen Hawking said, it gives us the ability to “read the mind of God.”

The entry is arbitrarily dated as 1984, the date of an important breakthrough in superstring theory by physicists Michael Green and John Schwarz. M-theory, an extension of string theory, was developed in the 1990s.

SEE ALSO Maxwell’s Equations (1861), String Theory (1919), Standard Model (1961), Quantum Electrodynamics (1948).

Particle accelerators provide information on subatomic particles to help physicists develop a Theory of Everything. Shown here is the Cockroft-Walton generator, once used at Brookhaven National Laboratory to provide the initial acceleration to protons prior to injection into a linear accelerator and then a synchrotron.



1987

Mitochondrial Eve • *Michael C. Gerald with Gloria E. Gerald*

Allan Wilson (1934–1991), **Rebecca L. Cann** (b. 1951), **Mark Stoneking** (b. 1956)

A 1987 paper in the prestigious journal *Nature* reported that "all mitochondrial DNA stems from one woman" and that she had lived in Africa some 200,000 years ago. The paper, authored by Rebecca L. Cann, Mark Stoneking, and their doctoral advisor, Allan Wilson, at the University of California, Berkeley, aroused intense interest and controversy for many reasons, and it continues to do so.

The authors referred to the samples they analyzed as "mitochondrial DNA," whereas the press dubbed them "mitochondrial Eve"—far more memorable, but also subject to misinterpretation. This Eve was not the single and only woman living at the time, as was said of the Eve of Genesis. In addition, the literal Biblical interpretation computed the age of humans to a time measured in thousands of years, not 200,000 years. Moreover, many evolutionists believed that humans evolved in separate parts of the world at about the same time, rather than the "Out of Africa" theory, in which anatomically modern humans originated in Africa and then migrated worldwide.

Cann and her colleagues analyzed mitochondrial DNA (mtDNA) and not nuclear DNA (nDNA), the latter responsible for transmitting the color of our eyes, racial characteristics, and susceptibility of certain diseases; mtDNA only codes for manufacturing proteins and performing other mitochondrial functions. Present in all cells of our body, nDNA is a merger of our mother's and father's DNA (recombination), whereas mtDNA is derived virtually exclusively from the maternal side with few if any mtDNA contributed from the sperm. Closely related individuals have almost identical mtDNA, with occasional mutations arising over thousands of years. It is assumed that the fewer the number of mutations, the shorter the period of time since common ancestors diverged.

Proponents of mitochondrial Eve do not suggest that this Eve was the first woman or only woman living at the time. Rather they estimate that some catastrophic event occurred, dramatically reducing Earth's population to some 10,000–20,000, and that only this Eve had an unbroken line of female descendants. Eve was said to be the most recent common ancestor from whom all living humans descended.

SEE ALSO Darwin's Theory of Natural Section (1859), Cellular Respiration (1937), Endosymbiont Theory (1967).

Adam and Eve, *completed c.1537 by the German Renaissance painter Lucas Cranach the Younger (1515–1586).*

1990

Domains of Life • *Michael C. Gerald with Gloria E. Gerald*

Carl Linnaeus (1707–1778), **Ernst Haeckel** (1834–1919), **C. B. van Niel** (1897–1985), **Roger Y. Stanier** (1916–1982), **Carl Woese** (1928–2012), **George E. Fox** (b. 1945)

An impetus for classification came during the seventeenth century when new plants and animals were arriving in Europe. In 1735, Carl Linnaeus, a pioneer in the science of taxonomy (also called *systematics*), developed a hierarchical system of biological nomenclature in which the highest rank, inclusive of all lower levels, was the *kingdom*, and these were two: animal and vegetable (plant). With the growing realization that unicellular organisms were unaccounted for, in 1866 Ernst Haeckel proposed the addition of a third kingdom, *Protista*.

In the 1960s, Roger Y. Stanier and C. B. van Niel devised a four-kingdom classification system based on the distinction between prokaryotic and eukaryotic cells, with the latter having a cell membrane enclosing its nucleus. Furthermore, they proposed a higher and more inclusive rank termed *superdomain* or *empire*. The Empire Prokarya encompassed the Kingdom Monera (bacteria), and the Empire Eukarya included the Kingdoms Plantae, Animalia, and Protista.

Until the mid-1970s, all classifications were based on the outward appearance of cells, namely their anatomy, morphology, embryology, and cell structure. In 1977, Carl Woese and George E. Fox at the University of Illinois at Urbana-Champaign classified organisms based on a comparison of their genes at a molecular level. In particular, they compared the nucleotide sequences in a subunit of ribosomal rRNA, the molecules that undergo evolutionary changes. In 1990, they introduced the concept of three domains of cellular life: the Domain Archaea, a disparate collection of prokaryotic organisms, among the most ancient found on Earth and capable of adapting to extreme environments (*extremophiles*); the Domain Bacteria; and the Domain Eukarya, which was subdivided into Kingdoms Fungi (yeasts, molds), Plantae (flowering plants, ferns), and Animalia (vertebrates, invertebrates). More recently, their Protista Kingdom has been subdivided into more discrete kingdoms. The final chapter on classification has not been written, with systems proposed that contain two to eight kingdoms.

SEE ALSO Linnaean Classification of Species (1735), Darwin's Theory of Natural Section (1859), Endosymbiont Theory (1967).

The rainbow colors in the Grand Prismatic Spring in Yellowstone National Park, Wyoming —the world's third largest hot spring—result from resident thermophilic microbes (extremophiles of the Kingdom Archaea) that favor temperatures ranging from 1,880°F (870°C) at the center to 1,470°F (640°C) at the rim.

1990

Hubble Telescope • *Clifford A. Pickover*

Lyman Strong Spitzer, Jr. (1914–1997)

"Since the earliest days of astronomy," write the folks at the Space Telescope Science Institute, "since the time of Galileo, astronomers have shared a single goal—to see more, see farther, see deeper. The Hubble Space Telescope's launch in 1990 sped humanity to one of its greatest advances in that journey." Unfortunately, ground-based telescope observations are distorted by the Earth's atmosphere that makes stars seem to twinkle and that partially absorbs a range of electromagnetic radiation. Because the Hubble Space Telescope (HST) orbits outside of the atmosphere, it can capture high-quality images.

Incoming light from the heavens is reflected from the telescope's concave main mirror (7.8 feet [2.4 meters] in diameter) into a smaller mirror that then focuses the light through a hole in the center of the main mirror. The light then travels toward various scientific instruments for recording visible, ultraviolet, and infrared light. Deployed by NASA using a space shuttle, the HST is the size of a Greyhound bus, powered by solar arrays, and uses gyroscopes to stabilize its orbit and point at targets in space.

Numerous HST observations have led to breakthroughs in astrophysics. Using the HST, scientists were able to determine the age of the universe much more accurately than ever before by allowing scientists to carefully measure distance to Cepheid variable stars. The HST has revealed protoplanetary disks that are likely to be the birthplaces of new planets, galaxies in various stages of evolution, optical counterparts of gamma-ray bursts in distance galaxies, the identity of quasars, the occurrence of extrasolar planets around other stars, and the existence of dark energy that appears to be causing the universe to expand at an accelerating rate. HST data established the prevalence of giant black holes at the centers of galaxies and the fact that the masses of these black holes are correlated with other galactic properties.

In 1946, American astrophysicist Lyman Spitzer, Jr. justified and promoted the idea of a space observatory. His dreams were realized in his lifetime.

SEE ALSO Telescope (1608), Hubble's Law of Cosmic Expansion (1929), Space Satellite (1957), Dark Energy (1998).

Astronauts Steven L. Smith and John M. Grunsfeld appear as small figures as they replace gyroscopes inside the Hubble Space Telescope (1999).

1990

World Wide Web • *Marshall Brain*

Robert Cailliau (b. 1947), **Tim Berners-Lee** (b. 1955)

In the mid-1980s, the Internet existed, and people were using it. The number of host computers connected to the Internet in 1987 was about 10,000. However, nearly every person using the Internet at that time was affiliated with the universities, companies, and research organizations that provided the host computers. The public had no access.

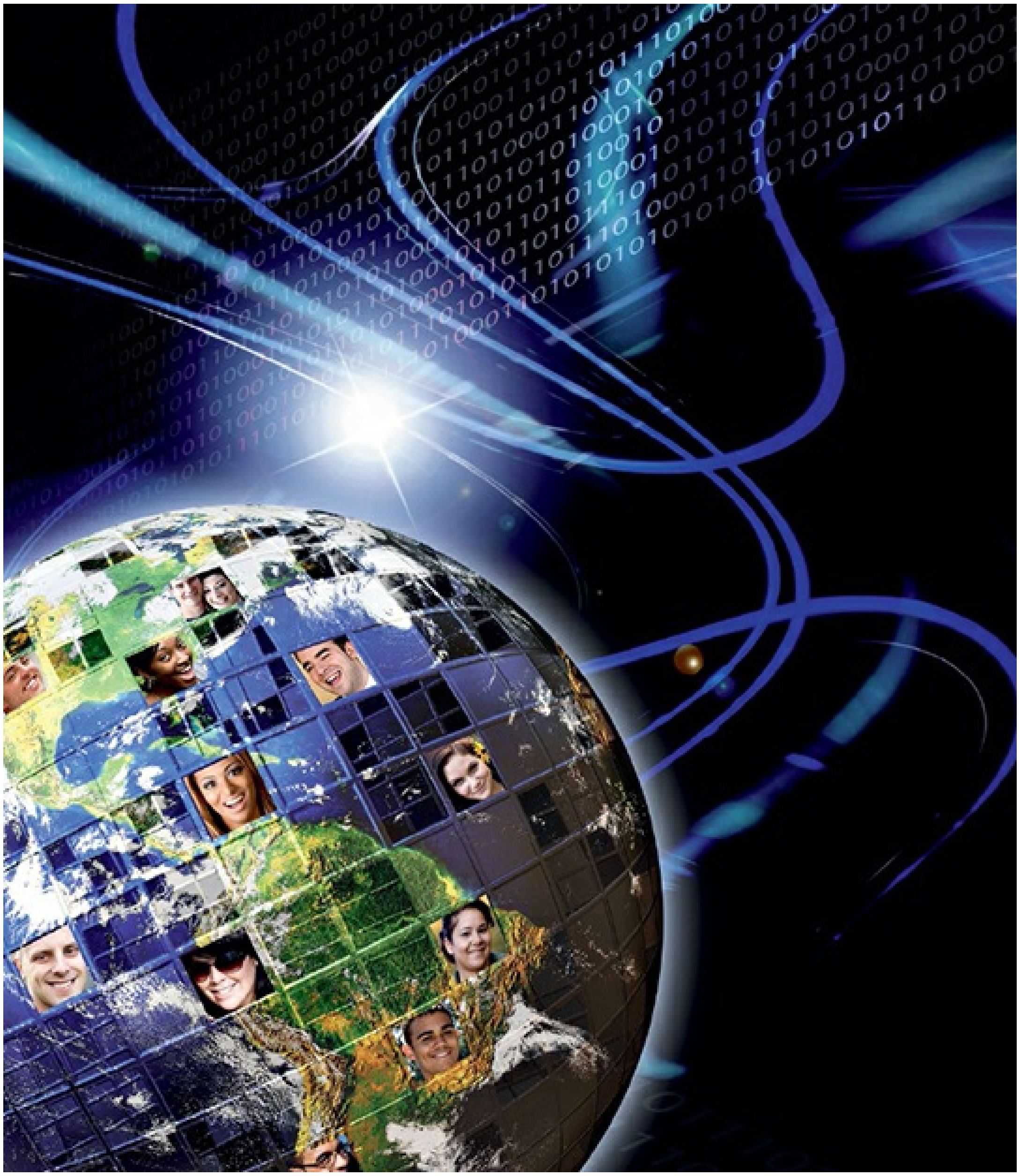
At this time, people were using a variety of Internet tools to move information around. E-mail and FTP (File Transfer Protocol) were two of the most common. A person could upload a file to a FTP server and then send e-mail to people telling them that they could download the file. People could connect to computers remotely using Telnet. It all worked, but the Internet was a bit technical and cumbersome.

Then, in 1990, everything began to change, when British computer scientist Tim Berners-Lee and Belgian computer scientist Robert Cailliau, proposed a "hypertext project" for the "WorldWideWeb." The World Wide Web was born, and it made the Internet incredibly easy to use as an information tool. On the one hand it was so simple, but on the other hand it was so incredibly powerful. As a result, the web has changed so many things, including the way goods are bought and sold, the way news and information are delivered, the way we educate people, the way people communicate. In addition, it utterly leveled the playing field. Suddenly, anyone could publish information to millions of people.

There were four core ideas that had to be engineered simultaneously for the web to work: 1) the web server, which holds web pages for people to access, 2) the web browser, which can gather and assemble web pages from servers so people can view them, 3) the web markup language, called HTML (Hypertext Markup Language), which allows people to create web pages, and 4) the web protocol, named HTTP (Hypertext Transfer Protocol), which allows for communication between server and browser. Once a web server existed with a web page in HTML on it, and someone had a web browser, the web was born. And then it spread like wildfire because engineers made accessing the Internet trivially easy.

SEE ALSO Telephone (1876), ENIAC (1946), ARPANET (1969).

The World Wide Web, for which resources such as Web pages are identified by URLs (Uniform Resource Locators), continues to change society in unprecedented ways.



1994

Global Positioning System (GPS) •

Marshall Brain

Ivan A. Getting (1912–2003), **Roger L. Easton** (1912–2014), **Bradford Parkinson** (b. 1935)

If you were an engineer working on the Global Positioning System (GPS), you were doing something incredible. You were proposing the creation of a new sense that could become available to every human being on the planet. Humans come equipped with the normal senses: vision, hearing, smell, taste, and touch. But humans definitely do not come equipped with a sense of direction, especially at night, especially on the open oceans, especially in bad weather where clouds, fog, and rain obscure every landmark.

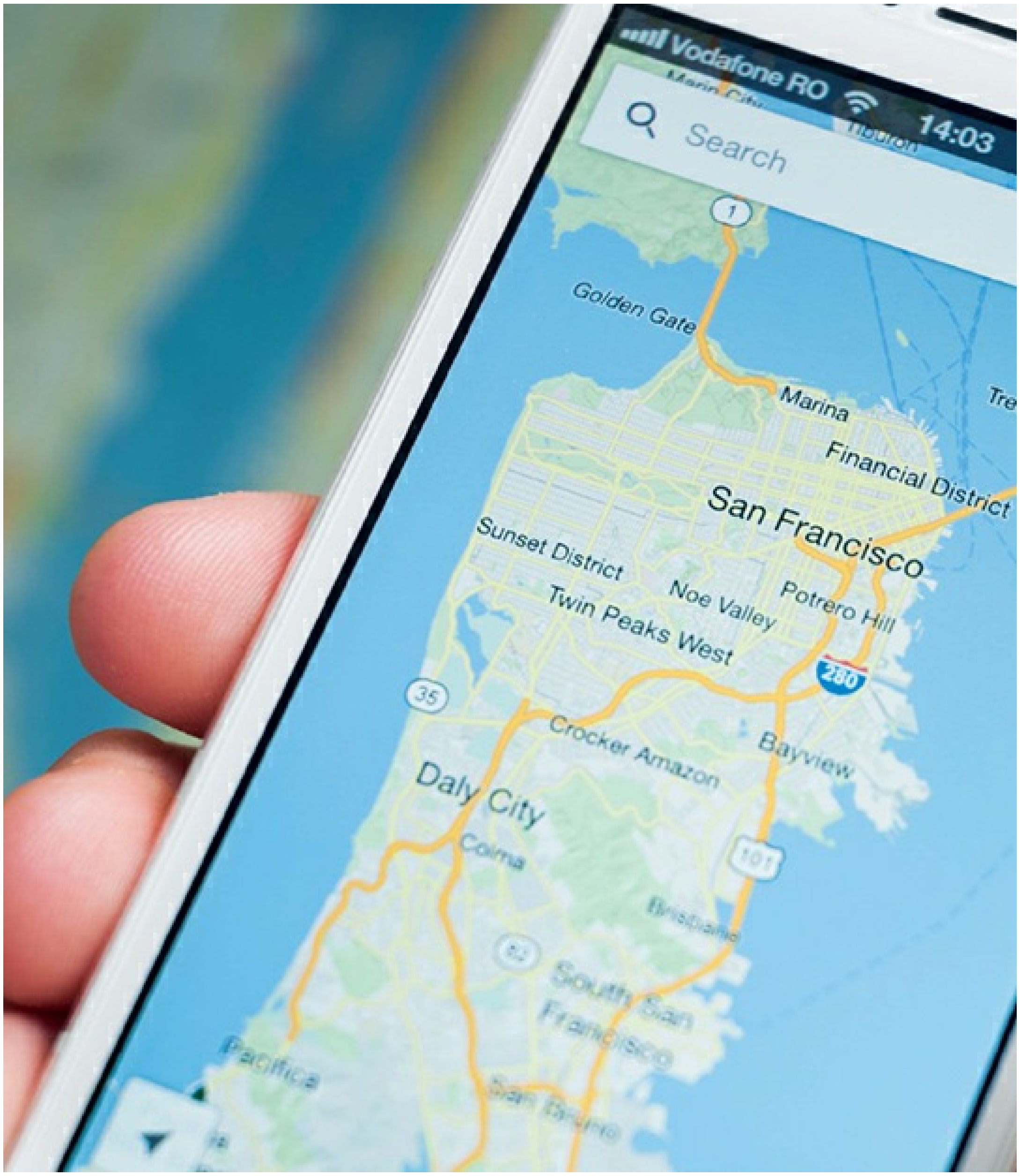
The GPS engineers, a team including Ivan Getting, Roger Easton, and Bradford Parkinson, who were working for the United States Department of Defense, proposed to change all of that. By 1994, they had created a ubiquitous, instantaneous, and precise system by which any human could locate his or her exact position on the planet with roughly 30-foot (10 meter) accuracy, anytime, anywhere.

One of the most audacious parts of the proposed system would be the cost—approximately $12 billion for a constellation of 24 satellites funded by the US military that went into orbit between 1989 and 1994. Another audacious part was the technology. This new GPS system demanded small, accurate atomic clocks that could operate unattended for years in orbit—two of them per satellite. These clocks are not simple devices. And then there was the technique the engineers devised to determine location. A GPS receiver would need to be able to see at least four satellites overhead, know exactly where each is in orbit, and then determine exactly how far away each one is. Using the distance and location of the four satellites, the receiver could triangulate its exact position and altitude on earth. It could also derive the exact time with atomic clock accuracy without needing to have its own atomic clock.

Here on Earth, the arrival of the cheap consumer GPS receiver combined with the arrival of the cheap, pocket cell phone to make it seem like we were living in the future. It is an amazing pair of capabilities for any human to have.

SEE ALSO Atomic Clocks (1955), Space Satellite (1957), Saturn V Rocket (1967).

Photo of the iPhone 5 smartphone running the Google Maps app (a Web-based service displaying street maps and more).


Vodafone RO
14:03
Search
1
Golden Gate
Marina
Financial District
San Francisco
Sunset District
Noe Valley
Potrero Hill
Twin Peaks West
280
35
Crocker Amazon
Bayview
Daly City
Colma
101

1998

Dark Energy • *Clifford A. Pickover*

“A strange thing happened to the universe five billion years ago,” writes science-journalist Dennis Overbye. “As if God had turned on an antigravity machine, the expansion of the cosmos speeded up, and galaxies began moving away from one another at an ever faster pace.” The cause appears to be dark energy—a form of energy that may permeate all of space and that is causing the universe to accelerate its expansion. Dark energy is so abundant that it accounts for nearly three-quarters of the total mass-energy of the universe. According to astrophysicist Neil deGrasse Tyson and astronomer Donald Goldsmith, “If cosmologists could only explain where the dark energy comes from . . . they could claim to have uncovered a fundamental secret of the universe.”

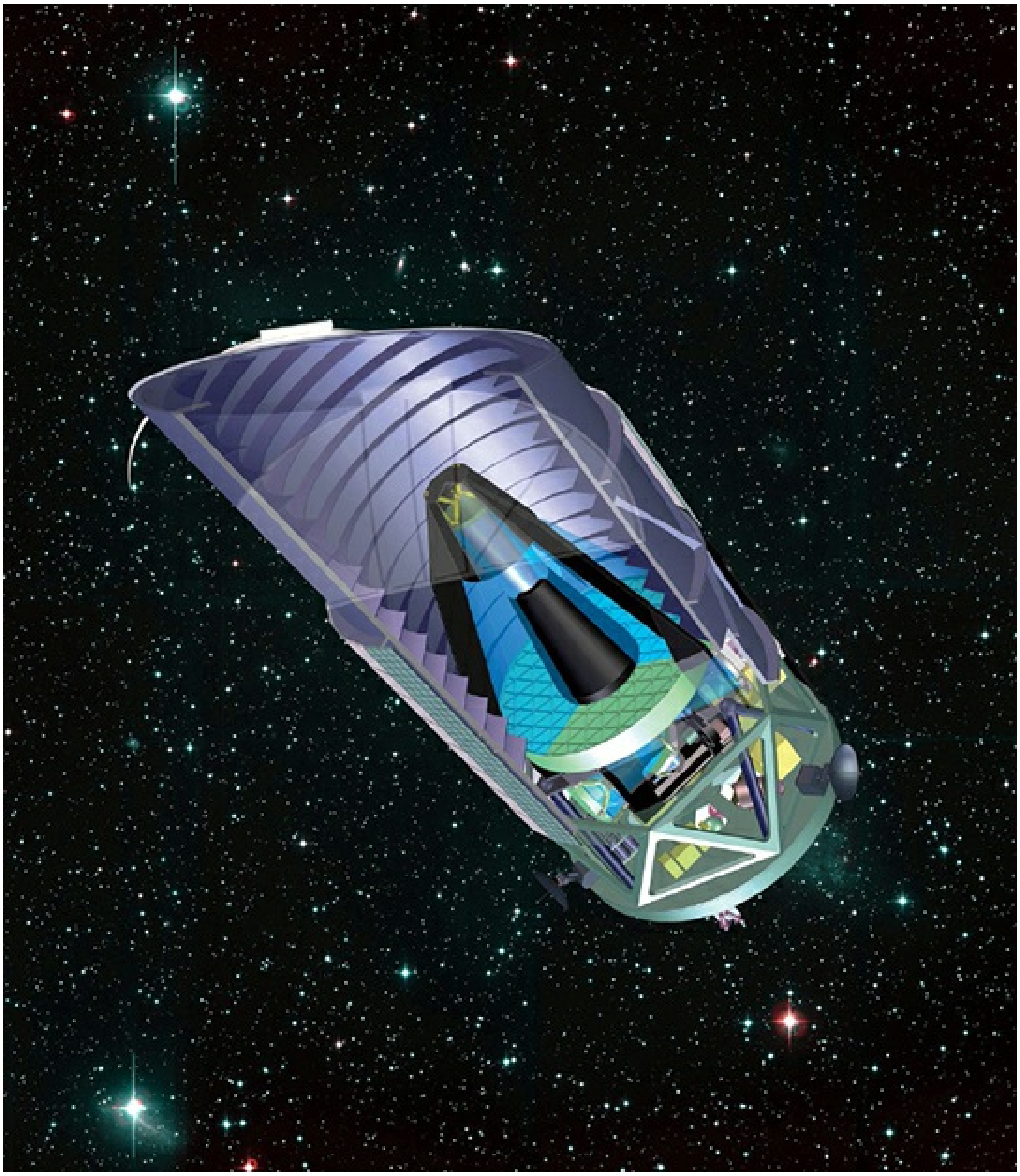
Evidence of the existence of dark energy came in 1998, during astrophysical observations of certain kinds of distant supernovae (exploding stars) that are receding from us at an accelerating rate. In the same year, American cosmologist Michael Turner coined the term *dark energy*.

If the acceleration of the universe continues, galaxies outside our local supercluster of galaxies will no longer be visible, because their recessional velocity will be greater than the speed of light. According to some scenarios, dark energy may eventually exterminate the universe in a cosmological Big Rip as matter (in forms that range from atoms to planets) is torn apart. However, even without a Big Rip, the universe may become a lonely place. Tyson writes, “Dark energy . . . will, in the end, undermine the ability of later generations to comprehend their universe. Unless contemporary astrophysicists across the galaxy keep remarkable records . . . future astrophysicists will know nothing of external galaxies. . . . Dark energy will deny them access to entire chapters from the book of the universe. . . . [Today] are we, too, missing some basic pieces of the universe that once was,

[thus] leaving us groping for answers we may never find?”

SEE ALSO Hubble’s Law of Cosmic Expansion (1929), Dark Matter (1933), Cosmic Microwave Background (1965), Cosmic Inflation (1980).

SNAP (which stands for Supernova Acceleration Probe, a cooperative venture between NASA and the U.S. Department of Energy) is a proposed space observatory for measuring the expansion of the Universe and for elucidating the nature of dark energy.



1998

International Space Station • *Jim Bell*

Early-twentieth-century rocket pioneers such as Konstantin Tsiolkovsky and Robert Goddard were among the first to work out the technical details of orbiting stations and habitats in space. For most of the century, however, the idea of a human outpost in Earth orbit was only realized in science fiction books, magazines, TV shows, and movies. In the 1970s the Soviet Union launched the first of nine long-duration *Salyut* space research modules, followed up in the 1980s by the orbital assembly of their *Mir* space station—the first long-duration, multicrew outpost in space.

NASA's plans to launch a US space station (called *Freedom*) in the 1980s never materialized, due to cost overruns and technical delays. The fall of the Soviet Union in 1991, technical problems with the *Mir* station, and the high cost of launching and operating space vehicles in general all compelled NASA, Russia, and other space-faring nations to pool resources toward the design and operation of a joint International Space Station (ISS), begun in 1993.

The first component of the new ISS was a Russian electrical power, propulsion, and storage module called *Zarya*, launched into low Earth orbit (about 230 miles [370 kilometers] above the surface) on a Russian Proton rocket in November 1998. The second component, a US docking, airlock, and research module called *Unity*, was launched and connected to *Zarya* a few weeks later by the crew of the space shuttle *Endeavour*. Fifteen more launches of shuttles and Russian Proton and Progress rockets over the next 13 years added additional solar panels, living quarters, laboratories, airlocks, and docking ports. Completed in 2011, the ISS now spans the area of a US football field, with a total mass of more than 920,000 pounds (420,000 kilograms), making it the largest artificial satellite ever constructed. In addition to the United States and Russia, the European, Japanese, and

Canadian space agencies are also key partners.

The ISS is primarily an international research laboratory designed to take advantage of its unique microgravity, orbital environment to enable space-related medical, engineering, and astrophysical research. But it also serves an important role as an outpost for a permanent human presence in space, a place where we can learn how to live and work there, and how best to prepare to venture further beyond low Earth orbit for deep space voyages of exploration.

SEE ALSO First Humans in Space (1961), First on the Moon (1969), *Spirit* and *Opportunity* on Mars (2004).

The International Space Station orbits about 190 miles (305 kilometers) above Earth's surface. Assembly of the space research outpost began in 1998; this 2009 photo taken by the crew of the space shuttle Discovery *shows the station's solar panels, trusses, and pressurized modules.*

2003

Human Genome Project • *Clifford A. Pickover*

James Dewey Watson (b. 1928), **John Craig Venter** (b. 1946), **Francis Sellers Collins** (b. 1950)

The Human Genome Project (HGP) is an international effort to determine the genetic sequence of the approximately three billion chemical base pairs in our DNA and to gain insight into its roughly 20,000 genes. Genes are units of heredity and embodied as stretches of DNA that code for a protein or an RNA molecule that has a particular function. The HGP began in 1990 under the leadership of American molecular biologist James Watson and, later, under American physician-geneticist Francis Collins. A parallel effort was conducted by American biologist Craig Venter, founder of Celera Genomics. Not only does this DNA sequence help us understand human disease, it also helps elucidate the relationship between humans and other animals.

In 2001, Collins spoke regarding the publication of a majority of the human genome: “It’s a history book: a narrative of the journey of our species through time. It’s a shop manual: an incredibly detailed blueprint for building every human cell. And it’s a transformative textbook of medicine: with insights that will give health-care providers immense new powers to treat, prevent, and cure disease.” A more complete sequence, announced in 2003, is considered to be a watershed moment in the history of civilization.

To help generate the human genetic sequence, the genome was first broken into smaller fragments, and these pieces were inserted into bacteria in order to make many copies and create a stable resource, or library, of DNA clones. Assembling the larger sequences from fragments required sophisticated computer analyses.

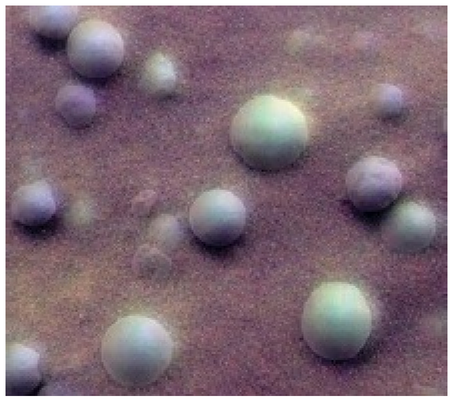
Except for identical twins, individual human genomes differ, and future research will continue to involve the comparison of sequences of different individuals to help scientists better understand the role of genetics in disease and differences among humans. Only about 1 percent of the genome's sequence codes for proteins. The number of genes in humans falls between the number for grape plants (~30,400 genes) and for chickens (~16,700 genes). Interestingly, nearly half of the human genome is composed of transposable elements, or jumping DNA fragments that can move around, on, and between chromosomes.

SEE ALSO Chromosomal Theory of Inheritance (1902), DNA Structure (1953), Epigenetics (1983), Polymerase Chain Reaction (1983).

Going beyond the HGP, results from the Neanderthal Genome Project allow researchers to compare human genomes to sequences from Neanderthals, our close evolutionary relatives who became extinct around 30,000 years ago.

2004

Spirit and *Opportunity* on Mars • *Jim Bell*



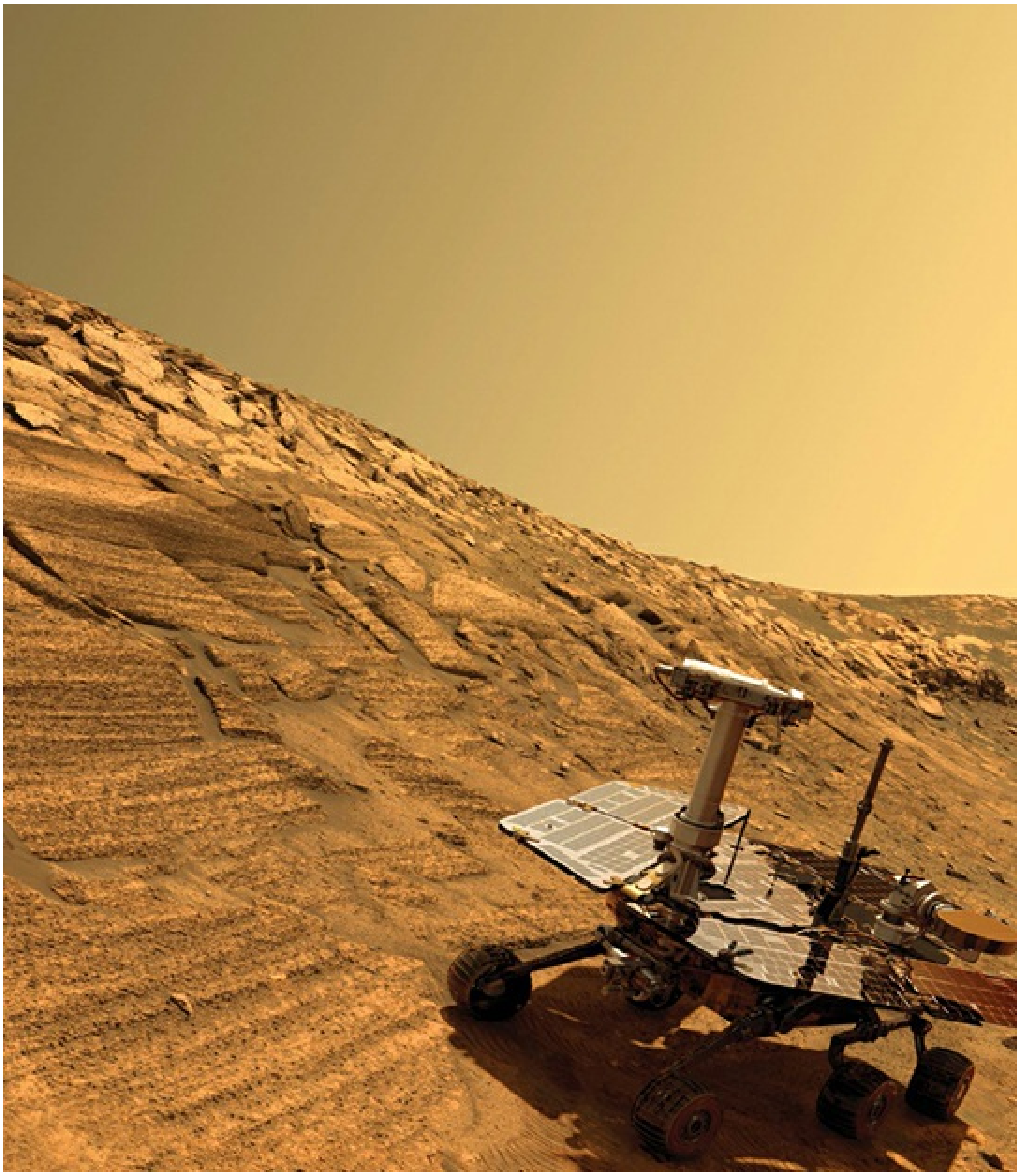
More than three decades of successful orbital and landed investigations of Mars by scientists involved in the Mariner and Viking missions painted a compelling picture of major past climate changes on the Red Planet. The Martian surface today is extremely cold, bone dry, and inhospitable to life as we know it. But ancient Mars, as revealed by these missions, appears to have been a warmer, wetter, and potentially more Earthlike place. If so, then early Mars (during the first billion years or so after its formation) may have been a habitable environment where, as on our own planet, life could have thrived.

Planetary scientists wanted to move beyond photographic evidence of a potentially habitable early Mars, however, and make quantitative geologic, geochemical, and mineralogic measurements that could provide smoking-gun proof. Experience gained from the 1997 Mars Pathfinder mission proved the value of mobility in doing geologic field work with robots in distant locations, leading to the choice to embark on an even longer-range rover mission. Because of two Mars missions failures in 1999, NASA decided to reduce its risk: instead of just one rover, it would launch twin rovers—named *Spirit* and *Opportunity*—in 2003.

Both rovers landed safely in early 2004 and began their separate adventures on opposite sides of the planet: *Spirit* in an ancient crater named Gusev, which may once have hosted a lake, and *Opportunity* in the cratered area Meridiani Planum, where Mars Global Surveyor data showed evidence for water-formed minerals. After several years of virtually roving around Gusev with *Spirit*, mission scientists discovered evidence of water-bearing minerals in an ancient hydrothermal system that provided smoking-gun evidence for past habitability in Gusev. At Meridiani, the team immediately found other water-bearing minerals and geologic clues that provided conclusive proof of past habitability there as well. *Spirit*'s last data came in early 2010, but as of mid-2012 *Opportunity* continues to roll on and make new discoveries.

SEE ALSO First Humans in Space (1961), First on the Moon (1969), International Space Station (1998).

A computer-generated version of the NASA Mars rover Opportunity *placed into an actual Opportunity Pancam mosaic of finely layered rocks inside Endurance crater. These rocks contain evidence of past liquid water on Mars, including millimeter-size iron-rich spheres (inset) called concretions.*



2008

Human Cloning • *Clifford A. Pickover*

Science educator Regina Bailey writes, "Imagine a world where cells can be created for therapeutic treatment of certain diseases or whole organs can be generated for transplants. . . . Humans could duplicate themselves or make exact copies of lost loved ones. . . . [Cloning and biotechnology] will define our time for future generations." In 2008, an ethical storm was already brewing when American scientist Samuel Wood became the first man to clone himself.

Reproductive human cloning refers to the production of a person who is essentially genetically identical to another. This may be accomplished by somatic cell nuclear transfer (SCNT), a process in which the nucleus of a donor adult cell is inserted into an egg cell whose nucleus has been removed, which may result in a developing embryo implanted in a womb. A new organism can also be cloned by splitting the early embryo, so that each portion becomes a separate organism (as happens with identical twins). With therapeutic human cloning, the clone is not implanted, but its cells serve a useful purpose, such as growing new tissues for transplantation. These patient-specific tissues do not trigger the immune response.

In 1996, Dolly, a sheep, became the first mammal to be successfully cloned from an adult cell. In 2008, Wood successfully created five embryos using DNA from his own skin cells, which might have been a source of embryonic stem cells used to repair injuries and cure diseases. Embryonic stem cells are capable of becoming any kind of cell in the human body. For legal and ethical reasons, the five embryos were destroyed. Following the news of human cloning, a Vatican representative condemned the act, stating, "This ranks among the most morally illicit acts." Other methods for collecting stem cells do not require cloning of embryos. For example, skin cells can be reprogrammed to create induced pluripotent stem cells (iPS), with no embryo needed, which might serve as possible sources for various replacement tissues destroyed by degenerative diseases.

SEE ALSO Discovery of Sperm (1678), Cell Division (1855), DNA Structure (1953), Gene Therapy (2016).

Long discussed in science fiction, human cloning may become relatively easy to accomplish in the future. A Vatican representative condemned early experiments as ranking "among the most morally illicit acts."

2009

Large Hadron Collider • *Clifford A. Pickover*

According to Britain's *The Guardian* newspaper, "Particle physics is the unbelievable in pursuit of the unimaginable. To pinpoint the smallest fragments of the universe you have to build the biggest machine in the world. To recreate the first millionths of a second of creation you have to focus energy on an awesome scale." Author Bill Bryson writes, "Particle physicists divine the secrets of the Universe in a startlingly straightforward way: by flinging particles together with violence and seeing what flies off. The process has been likened to firing two Swiss watches into each other and deducing how they work by examining their debris."

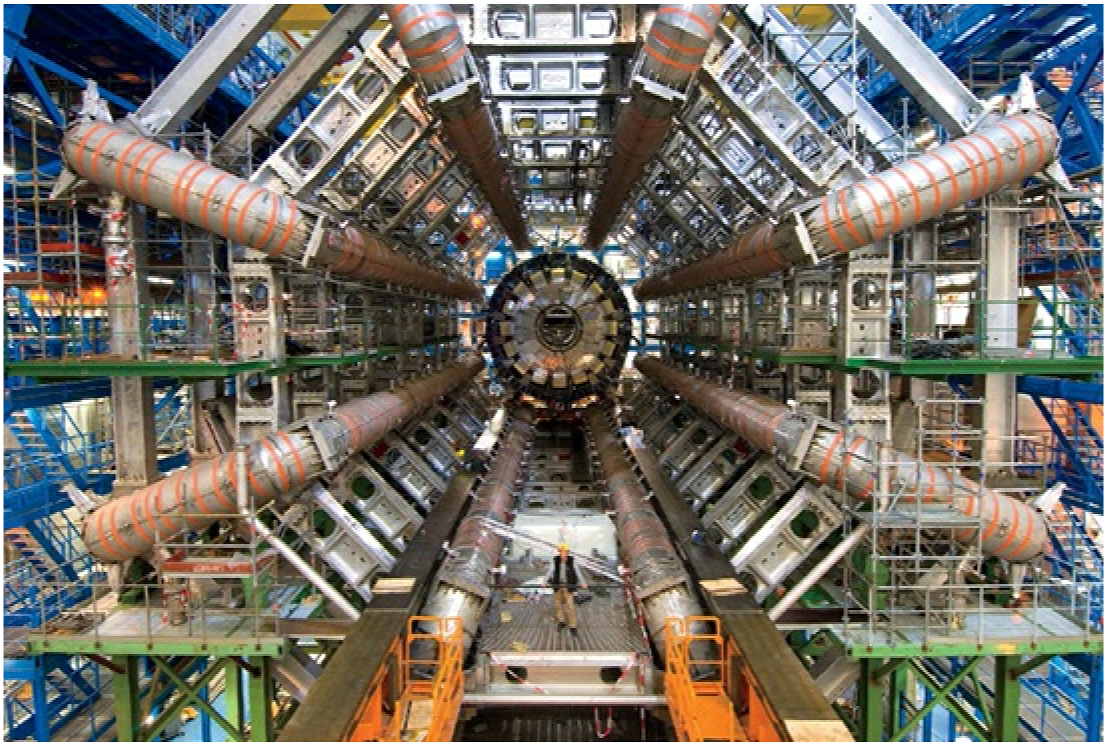
Built by the European Organization for Nuclear Research (usually referred to as CERN), the Large Hadron Collider (LHC) is the world's largest and highest-energy particle accelerator, designed primarily to create collisions between opposing beams of protons (which are one kind of hadron). The beams circulate around the circular LHC ring inside a continuous vacuum guided by powerful electromagnets, the particles gaining energy with every lap. The magnets exhibit superconductivity and are cooled by a large liquid-helium cooling system. When in their superconduction states, the wiring and joints conduct current with very little resistance.

The LHC resides within a tunnel 17 miles (27 kilometers) in circumference across the Franco-Swiss border and allows physicists to gain a better understanding of the Higgs boson (also called the God particle), a particle that explains why particles have mass. The LHC may also be used to find particles predicted by supersymmetry, which suggests the existence of heavier partner particles for elementary particles (for example, selectrons are the predicted partners of electrons). Additionally, the LHC may be able to provide evidence for the existence of spatial dimensions beyond the three obvious spatial dimensions. In some sense, by colliding the two beams, the

LHC is re-creating some of the kinds of conditions present just after the Big Bang. Teams of physicists analyze the particles created in the collisions using special detectors. In 2009, the first proton–proton collisions were recorded at the LHC.

SEE ALSO Superconductivity (1911), String Theory (1919), Standard Model (1961).

Installing the ATLAS calorimeter for the LHC. The eight toroid magnets can be seen surrounding the calorimeter that is subsequently moved into the middle of the detector. This calorimeter measures the energies of particles produced when protons collide in the center of the detector.



2016

Gene Therapy • *Clifford A. Pickover*

William French Anderson (b. 1936)

Many diseases result from defects in our genes, which are our units of heredity that control traits ranging from eye color to our susceptibility to **cancer** and asthma. For example, **sickle-cell anemia**, which produces abnormal red blood cells, arises from a single deleterious change in the DNA sequence of a gene.

Gene therapy is a young discipline that involves the insertion, alteration, or removal of genes in human cells to treat disease. One form of gene therapy involves the use of a virus that is engineered to contain a useful human gene. The virus inserts this gene into a defective human cell (usually at a random location in the host's DNA), and this new gene manufactures a properly functioning protein. If a **sperm** or egg were modified, the change would be passed to offspring, with profound ethical implications for the human race.

The first approved gene therapy procedure in the United States occurred in 1990, to treat a four-year-old girl who was suffering from a rare immune disorder known as adenosine deaminase (ADA) deficiency that made her vulnerable to infections. American researcher W. French Anderson and colleagues treated white blood cells withdrawn from her body with the gene she lacked, returned the cells to her body, and hoped the cells would produce the enzyme she needed. Although the cells safely produced the enzyme, the cells failed to give rise to healthy new cells. Gene therapy was later used to successfully treat ADA deficiency, other forms of severe immune deficiency (e.g., "bubble boy" disease), AIDS (by genetically altering T cells to resist HIV viruses), and Parkinson's disease (by reducing symptoms). Nevertheless, the procedure carries risks in some cases. Several of the children in an immune deficiency study contracted leukemia, since viral insertion of genes into a host cell can sometimes disrupt normal gene function. Also, the viral carriers of the genes (or the cells that harbor the newly implanted gene) may be attacked by the host immune's system, rendering the treatment ineffective. At worst, a strong immune attack can kill a patient.

More recently, CRISPR technology allows researchers to make more precise genetic changes at exact locations in an organism's genome. In 2016, the US Food and Drug Administration approved the first human trial for CRISPR to be used in cancer therapy, involving editing patients' T cells, which play a role in immunity.

SEE ALSO Epigenetics (1983), Polymerase Chain Reaction (1983), Human Cloning (2008).

Hemophilia is caused by a mutation in a single gene on the X chromosome. Hemophiliacs bleed profusely when cut. Show here is Queen Victoria of the United Kingdom (1819–1901), who passed this mutation to numerous royal descendants.

2016

Gravitational Waves • *Jim Bell*

In the view of the universe elegantly advocated by Albert Einstein in his early twentieth-century theory of general relativity, our three dimensions of space and one dimension of time are intimately linked into a continuum called "spacetime." Furthermore, Einstein and others realized that spacetime can become warped or curved in the presence of mass or energy, and thus ripples or waves could theoretically propagate through spacetime like the waves on a pond.

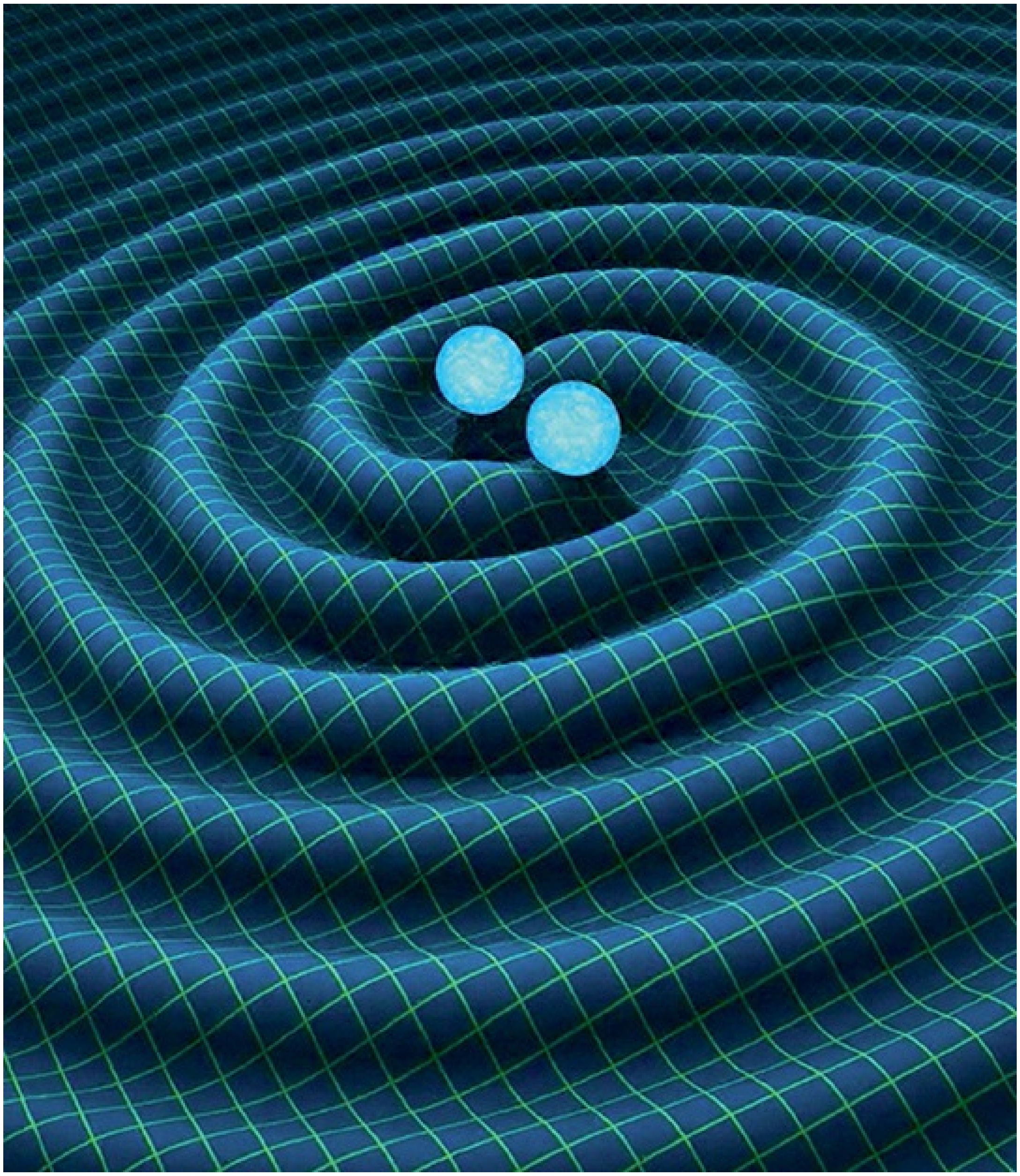
At least, that is theoretically the case. The problem scientists encountered throughout the rest of the twentieth century, however, was that the magnitude of these predicted gravitational waves in the spacetime continuum was extremely small and impossible to detect with existing technology. In addition, the kinds of events or disturbances that could produce detectable gravitational waves—like the supernova explosion of an enormously massive star, or the merger of two black holes—are rare and/or extremely distant. Thus, detecting gravitational waves had to wait for technological advances.

Those advances finally arrived with the advent of two enormous detectors specially designed to search for gravitational waves: the US Laser Interferometer Gravitational-wave Observatory (LIGO) and the European Virgo Interferometer. Both facilities use lasers to search for the tiny changes in the distances between reference targets that would be caused by a passing gravitational wave. The instruments can achieve exquisite sensitivity, comparable to being able to measure the distance to the nearest stars to within an accuracy of a human hair. LIGO began operations in 2002 and Virgo in 2003, and since 2007 both facilities have jointly shared their data and analyses, helping to refute or confirm each other's potential detections.

After more than a decade of searching, and after careful data processing and peer review of their results, LIGO and Virgo finally announced the first detection of gravitational waves (from the merger of two supermassive black holes) in February 2016, confirming the last major unproven prediction of Einstein's theory of general relativity. More detections have been made since, and astronomers are now excited to use gravitational waves as new tools to study extremely violent and high-energy phenomena across the universe.

SEE ALSO Newton's Laws (1687), Einstein's "Miracle Year" (1905), Black Holes (1965), Hawking's "Extreme Physics" (1965), Gravitational Lensing (1979).

Computer simulation of ripples in the spacetime continuum—gravitational waves—caused by the merger of two supermassive, co-orbiting black holes.



2017

Proof of the Kepler Conjecture • *Clifford A. Pickover*

Johannes Kepler (1571–1630), **Thomas Callister Hales** (b. 1958)

Imagine that your goal is to fill a large box with as many golf balls as possible. Close the lid tightly when finished. The density of balls is determined from the proportion of the volume of the box that contains a ball. In order to stuff the most balls into the box, you need to discover an arrangement with the highest possible density. If you simply drop balls into the box, you'll only achieve a density of roughly 65 percent. If you are careful, and create a layer at the bottom in a hexagonal arrangement, and then put the next layer of balls in the indentations created by the bottom layer, and continue, you'll be able to achieve a packing density of $\pi/\sqrt{18}$, which is about 74 percent.

In 1611, German mathematician and astronomer Johannes Kepler wrote that no other arrangement of balls has a higher average density. In particular, he conjectured in his monograph *The Six-Cornered Snowflake* that it is impossible to pack identical spheres in three dimensions greater than the packing found in face-centered (hexagonal) cubic packing. In the nineteenth century, Karl Friedrich Gauss proved that the traditional hexagonal arrangement was the most efficient for a *regular* 3-D grid. Nevertheless, the Kepler conjecture remained, and no one was sure if a denser packing could be achieved with an *irregular* packing.

Finally, in 1998, American mathematician Thomas Hales stunned the world when he presented a proof that Kepler had been right. Hales's equation and its 150 variables expressed every conceivable arrangement of 50 spheres. Computers confirmed that no combination of variables led to a packing efficiency higher than 74 percent.

The *Annals of Mathematics* agreed to publish the proof, provided it was accepted by a panel of 12 referees. In 2003, the panel reported that they were "99 percent certain" of the correctness of the proof. Finally, in 2017, the *Forum of Mathematics, Pi* journal published a formal proof of the Kepler Conjecture, by a team led by Hales, resolving a problem that was unsolved for hundreds of years.

SEE ALSO Reimann Hypothesis (1859), Proof of the Prime Number Theorem (1896), Hilbert's 23 Problems (1900).

Fascinated by Kepler's famous conjecture, Princeton University scientists Paul Chaikin, Salvatore Torquato, and colleagues studied the packing of M&M chocolate candies. They discovered that the candies had a packing density of about 68 percent, or 4 percent greater than for randomly packed spheres.

Notes and Further Reading

c. 18,000 BCE, **Ishango Bone**

Bogoshi, J., Naidoo, K., Webb, J., *Math. Gazette*, 71:294; 1987.

Teresi, D., *Lost Discoveries*, Simon & Schuster, 2002.

c. 11,000 BCE, **Wheat: The Staff of Life**

Kirby, E. J. M., Food and Agricultural Organization of the United Nations—Botany of the Wheat Plant.

c. 10,000 BCE, **Agriculture**

Denison, R. F., *Darwinian Agriculture: How Understanding Evolution Can Improve Agriculture*. Princeton, NJ: Princeton University Press, 2012.

c. 10,000 BCE, **Domestication of Animals**

Manning, A., et al., *Animals and Human Society: Changing Perspectives*. New York: Routledge, 1994.

c. 7000 BCE, **Rice Cultivation**

Tsunoda, S. (ed.), *Biology of Rice*. New York: Elsevier Science (1984).

c. 5000 BCE, **Birth of Cosmology**

According to an official NASA definition, *cosmology* is the study of the structure and changes in the present universe, whereas the study of the origin and evolution of the early universe is technically called *cosmogony*.

c. 3300 BCE, **Bronze**

Ekserdjian, D., ed. *Bronze*. London: Royal Academy of Arts, 2012.

Radivojevíc et al. “Tainted Ores and the Rise of Tin Bronzes in Eurasia.” *Antiquity* 87 (2013): 1030.

Sherby, O. D., and J. Wadsworth. “Ancient Blacksmiths, the Iron Age, Damascus Steels, and Modern Metallurgy.” U.S. Department of Energy, September 11, 2011, *https://e-reports-ext.llnl.gov/pdf/238547.pdf*.

c. 3000 BCE, **Dice**

Hayes, B., *Am. Scient.* 89:300;2001.

3000 BCE, Sutures

Kirkup, J. The Evolution of Surgical Instruments, Novato, CA: Norman, 2006.

c. 2500 BCE, **Egyptian Astronomy**

The author remembers reading an early edition of E.C. Krupp's *Echoes of the Ancient Skies: The Astronomy of Lost Civilizations* (Mineola, NY: Dover Publications, 2003) when he was young and being fascinated by how much the objects and motions of the sky meant to our distant ancestors.

c. 1650 BCE, **Rhind Papyrus**

Eves, H., *Great Moments in Mathematics (Before 1650)*, The Mathematical Association of America, Washington, D.C., 1983.

Robins, G., Shute, C., *The Rhind Mathematical Papyrus*, Dover Publications, NY, 1990.

c. 1300 BCE, **Iron Smelting**

Hosford, W. G. *Iron and Steel*. New York: Cambridge Univ. Press, 2012.

Sherby, O. D., and J. Wadsworth. "Ancient Blacksmiths, the Iron Age, Damascus Steels, and Modern Metallurgy." U.S. Department of Energy, September 11, 2011, https://e-reports-ext.llnl.gov/pdf/238547.pdf.

c. 1000 BCE, **Olmec Compass**

Carlson, J., *Science*, 189: 753; 1975.

c. 600 BCE, **Pythagorean Theorem and Triangles**

Loomis, E., *Pythagorean Proposition*, Washington, D.C.: Natl. Council of Teachers of Math., 1972.

Maor, E., *The Pythagorean Theorem*, Princeton University Press, 2007.

c. 600 BCE, **Sewage Systems**

IN.gov, *tinyurl.com/482p73f*.

c. 350 BCE, **Aristotle's *Organon***

SparkNotes, *tinyurl.com/5qhble*.

c. 350 BCE, **Platonic Solids**

Platonic solids are convex polyhedrons. A polyhedron is *convex* if for every pair of points that belong to the shape, the shape contains the whole straight line segment connecting the two points. Some astrophysicists have suggested

that our entire universe may be in the form of a dodecahedron.

c. 300 BCE **Euclid's *Elements***

Boyer, C., Merzbach, U., *A History of Mathematics*, John Wiley & Sons, 1991.

c. 240 BCE, **Eratosthenes Measures the Earth**

Hubbard, D., *How to Measure Anything*, Hoboken, NJ, 2007.

c. 230 BCE, **Pulley**

Haven, K., *100 Greatest Science Inventions of All Time*, Westport, CT: Libraries Unlimited, 2005.

c. 125 BCE, **Antikythera Mechanism**

Marchant, J., *tinyurl.com/ca8ory*.

c. 126 CE, **Roman Concrete**

Brandon, C. J., et. al. *Building for Eternity*. Oxford: Oxbow Books, 2014.

Pruitt, S. "The Secret of Ancient Roman Concrete." *History in the Headlines* (blog), June 21, 2013, *www.history.com/news/the-secrets-of-ancient-roman-concrete*.

c. 650, Zero

Arsham, *http://tinyurl.com/y7rcvhen*.

c. 850, Gunpowder

Kelly, J. *Gunpowder: Alchemy, Bombards, and Pyrotechnics*. New York: Basic Books, 2004.

Partington, J. R. *A History of Greek Fire and Gunpowder*. Cambridge: W. Heffer, 1960.

1202, Fibonacci's Liber Abaci

Today, many authors begin the Fibonacci sequence with a 0, as in 0, 1, 1, 2, 3. . . . Note that the number of columns in mammalian microtubule is typically a Fibonacci number.

1284, Eyeglasses

In 1268, R. Bacon used scientific principles to show that lenses could be used to correct vision.

Magner, L., *A History of the Life Sciences*, NY: Marcel Dekker, 1979.

c. 1500, Early Calculus

The figure is adapted from Ramasubramanian, K., et al., "Modification of the Earlier Indian Planetary Theory by the Kerala Astronomers (c. 1500) and the Implied Heliocentric Picture of Planetary Motion" (*Current Science*, vol. 66, 784–790, 1994).

1509, Golden Ratio

The origin of the term *golden ratio* is disputed but appears to have emerged in the twelfth century. Although the recent history of the golden ratio was triggered by Luca Pacioli's *Divina Proportione* (1509), ancient Greek mathematicians studied the ratio much earlier because it frequently appeared in geometrical studies. Note that the artistic figure for this entry depicts a Fibonacci spiral, based on consecutive terms of a Fibonacci sequence. Because the ratios of consecutive terms in the Fibonacci series approach ø, the two spirals are quite similar in appearance.

1543, De Humani Corporis Fabrica

Adler, R., *Medical Firsts*, Hoboken, NJ: John Wiley & Sons, 2004.

Saunders, J., O'Malley, C., *The Illustrations from the Works of Andreas Vesalius of Brussels*, NY: Dover Publications, NY, 1973.

1543, Sun-Centered Universe

O'Connor, J., Robertson, *http://tinyurl.com/pkglrpa*.

1545, Paré's "Rational Surgery"

Keynes, G., *The Apologie and Treatise of Ambroise Paré*, London: Falcon, 1951.

1608, Telescope

Lang, K., *tinyurl.com/yad22mv*.

Brockman, J., ed., *The Greatest Inventions of the Past 2000 Years*, NY: Simon & Schuster, 2000.

1609, Kepler's Laws of Planetary Motion

Gingerich, O., *Dictionary of Scientific Biography*, Gillispie, C., ed., NY: Scribner, 1970.

1614, Logarithms

Gibson, G., "Napier and the Invention of Logarithms," in *Handbook of the Napier Tercentenary Celebration*, E. M. Horsburgh, ed., Los Angeles:

Tomash Publishers, 1982.
Tallack, P., *The Science Book*, Weidenfeld & Nicholson, 2003.

1620, Scientific Method

Beveridge, W. I. B., *The Art of Scientific Investigation*. Caldwell, NJ: Blackburn, 2004.
Wilson, Jr., E. B., *An Introduction to Scientific Research*. Mineola, NY: Dover Publications, 1991.

1621, Slide Rule

F. Cajori writes, "It is by no means clear that Delamain [the student] stole the invention from Oughtred; Delamain was probably an independent inventor."

Cajori, F., *William Oughtred*, Chicago: Open Court, 1916.
Oughtred Society, *oughtred.org*.
Stoll, C., *Sci. Am.* 294:81; 2006.

1628, Circulatory System

The hearts of cold-blooded animals, such as eels, were useful to Harvey because their hearts beat more slowly than mammalian hearts and allowed more careful observation. Harvey also showed that the pulse was caused not directly by the motion of the arteries but rather by a passive response from pressures caused by heart contractions. Other researchers also theorized about blood circulation, including M. Servetus, R. Columbus (also Colombo), and A. Cesalpino.

Adler, R., *Medical Firsts*, Hoboken, NJ: John Wiley & Sons, 2004.

1637, Descartes' *La Géométrie*

Boyer, C., Merzbach, U., *A History of Mathematics*, John Wiley & Sons, 1991.
Grabiner, J., *Math. Mag.* 68:83, 1995.
Gullberg, J., *Mathematics*, W.W. Norton & Company, 1997.

1638, Acceleration of Falling Objects

Other earlier researchers into the acceleration of falling bodies include Nicole Oresme and Domingo de Soto.

1639, Projective Geometry

Other prominent people of the fifteenth and early sixteenth centuries who advanced the mathematical theory of perspective were P. Francesca, L. da

Vinci, and A. Dürer.

1654, Pascal's Triangle

Gordon, J. et al., *Phys. Rev. Lett.* 56:2280;1986.

1660, Von Guericke's Electrostatic Generator

Brockman, J., ed., *The Greatest Inventions of the Past 2000 Years*. New York: Simon & Schuster, 2000.

Gurstelle, W., *Adventures from the Technology Underground*. New York: Three Rivers Press, 2006.

1665, Development of Modern Calculus

In 1671, Newton wrote *On the Methods of Series and Fluxions*. (Fluxion was Newton's term for derivative in the field of calculus.) This work, although circulated in a manuscript to several peers in 1671, did not appear in print until 1736.

1665, *Micrographia*

Westfall, R., *Dictionary of Scientific Biography*, Gillispie, C., ed., NY: Scribner, 1970.

1668, Refuting Spontaneous Generation

Farley, J., *The Spontaneous Generation Controversy from Descartes to Oparin*. Baltimore: The Johns Hopkins Press, 1977.

1672, Measuring the Solar System

Haven, K., *100 Greatest Science Inventions of All Time.* Westport, CT: Libraries Unlimited, 2005.

1672, Newton's Prism

Douma, M., *http://tinyurl.com/ybu2k7j*.

1678, Discovery of Sperm

Some religious people wondered why God would be so wasteful of the homunculi, with so many preformed humans dying.

1687, Newton as Inspiration

Cropper, W., *Great Physicists*, NY: Oxford University Press, 2001.

Gleick, J., *Isaac Newton*, NY: Vintage, 2004.

Koch, R., Smith, C., New Scientist, 190: 25; 2006.

Hawking, S., *Black Holes and Baby Universes*, NY: Bantam, 1993.

1727, Euler's Number, *e*

The mathematical constant e is special for many reasons, e.g., $f(x)=e^x$ is its own derivative.

Darling, D., *The Universal Book of Mathematics*, John Wiley & Sons, 2004.

Kasner, E., Newman, J., *Mathematics and the Imagination*, Dover Publications, NY, 2001.

Maor, Eli, *e: The Story of a Number*, Princeton University Press, 1998.

1733, Normal Distribution Curve

Galton, F., *Natural Inheritance*, London: Macmillan, 1889.

1735, Linnaean Classification of Species

Blunt, W., et al., *Linnaeus: The Compleat Naturalist*. Princeton, NJ: Princeton University Press, 2002.

1760, Artificial Selection (Selective Breeding)

Wood, R. J., et al., *Genetic Prehistory in Selective Breeding: A Prelude to Mendel*. New York: Oxford University Press, 2001.

1761, Bayes' Theorem

Some historians feel that English mathematician Nicholas Saunderson may have discovered Bayes' theorem before Bayes.

1761, Causes of Cancer

Bloom, J., *Texas Monthly* 6:175; 1978.

1761, Morgagni's "Cries of Suffering Organs"

Simmons, J., *Doctors & Discoveries*, Boston: Houghton Mifflin, 2002.

1783, Black Holes

Quantum physics suggests that short-lived pairs of particles are created in space, and these pairs flicker in and out of existence in very short time scales. The process by which a black hole emits particles involves the creation of virtual particle pairs right on the edge of the black hole's horizon. The black hole's tidal gravity pulls the pair of virtual photons apart, thereby feeding energy into them. One member of the pair is swallowed by the black hole, and the leftover particle scoots away out into the universe

1797, Fundamental Theorem of Algebra

Dunham, W., *College Math. J.* 22:282;1991.

1798, Smallpox Vaccination

Despite his success, Jenner did not know of the cellular mechanism of immunity, which involves white blood cells. Initially, his work was attacked and ridiculed.

Mulcahy, R., *Diseases*, Minneapolis, MN: Oliver Press, 1996.
Riedel, S., *Proc. Bayl. Univ. Med.* Cent. 18:21; 2005.

1800, Battery

Brain, M., Bryant, C., *tinyurl.com/a2vpe*.
Guillen, M., *Five Equations that Changed the World*, NY: Hyperion, 1995.

1800, High-Pressure Steam Engine

Kirby, R., *Engineering in History*, Mineola, NY: Dover Publications, 1990.

1801, Wave Nature of Light

Tallack, P., ed., *The Science Book*, London: Weidenfeld & Nicolson, 2001.
Moring, G., *The Complete Idiot's Guide to Understanding Einstein*, NY: Alpha, 2004.

1807, Fourier Series

Jeans, J., *Science and Music*, Dover Publications, NY, 1968.
Ravetz, J., Grattan-Guinness, I., "Fourier," in *Dictionary of Scientific Biography*, Gillispie, C., ed., NY: Scribner, 1970.

1812, Laplace's *Théorie Analytique des Probabilités*

Hawking, S., *God Created the Integers*, Running Press, 2005.
Richeson, A., *Natl. Math. Mag.* 17:73; 1942.

1822, Babbage Mechanical Computer

Norman, J., *From Gutenberg to the Internet*, Novato, CA: Historyofscience.com, 2005.
Swade, D., *Sci. Am.* 268:86; 1993.

1824, Greenhouse Effect

Friedman, T., *Hot, Flat, and Crowded*, NY: Farrar, Straus and Giroux, 2008.
Gonzalez, J., Werthman, T., Sherer, T., *The Complete Idiot's Guide to Geography*, NY: Alpha, 2007.
Sagan, C., *Billions and Billions*, NY: Ballantine, 1998.
Tallack, P., ed., *The Science Book*, London: Weidenfeld & Nicolson, 2001.

1827, Brownian Motion

Other early researchers who worked in the area of Brownian motion include T. N. Thiele, L. Bachelier, and J. Ingenhousz.

1828, Germ-Layer Theory of Development

Gilbert, S., *Developmental Biology*. Sunderland, MA: Sinauer Associates, 2013.

McGeady, T. A., et al., *Veterinary Embryology*. Oxford, UK: Blackwell, 2006.

1829, Blood Transfusion

Hurt, R., *The History of Cardiothoracic Surgery*, Pearl River, NY: Parthenon, 1996.

1829, Non-Euclidean Geometry

Tallack, P., *The Science Book*, Weidenfeld & Nicholson, 2003.

1831, Cell Nucleus

Misteli, T. et al., *The Nucleus*. Cold Spring Harbor, NY: Cold Spring Harbor Laboratory Press, 2010.

1831, Darwin and the Voyages of the *Beagle*

Darwin, C., *The Voyage of the Beagle* (many editions)

Moorehead, A., *Darwin and the Beagle: Charles Darwin as Naturalist on the HMS Beagle Voyage*. New York: Harper & Row, 1970.

1836, Fossil Record and Evolution

Switek, B., *Written in Stone: Evolution, the Fossil Record, and Our Place in Nature*. New York: Bellevue Literary Press, 2010.

Taylor, T. N, et al., *Paleobotany: The Biology and Evolution of Fossil Plants.* New York: Academic Press, 2008.

1837, Nitrogen Cycle and Plant Chemistry

Stevenson, F. J., et al., *Cycles of Soil: Carbon, Nitrogen, Phosphorus, Sulfur, Micronutrients*. New York: John Wiley & Sons, 1999.

1837, Telegraph System

Connected Earth, *http://tinyurl.com/lgntn64*.

1839, Daguerreotype

Daguerreian Society. "About the Daguerreian Society,"

daguerre.org/index.php.
Wooters, D., and T. Mulligan, eds. *A History of Photography: The George Eastman House Collection*. London: Taschen, 2005.

1839, Rubber

Goodyear Tire & Rubber Company. "The Charles Goodyear Story," www.goodyear.com/corporate/history/history_story.html.

Korman, R. *The Goodyear Story*. San Francisco: Encounter Books, 2002.

1842, General Anesthesia

In 1842, a student, W. Clarke, used ether to assist in a tooth extraction. The precise molecular effect of anesthesia is still a subject of research, and it appears that anesthetics affect the spinal cord and brain.

1843, Conservation of Energy

Angier, N., *The Canon*, NY: Houghton Mifflin, 2007.
Trefil, J., *The Nature of Science*, NY: Houghton Mifflin, 2003.

1847, Semmelweis's Hand Washing

The lethal *Streptococcus* bacteria of septicemia could invade the uterus, which was made vulnerable and exposed by childbirth. Semmelweis referred to the cause as cadaverous particles. American physician O. W. Holmes Sr. also argued that puerperal fever spread from patient to patient via physician contact, and he suggested that physicians clean their instruments.

Carter, K., Carter, B., *Childbed Fever*, New Brunswick, NJ: Transaction Publishers, 2005.

1850, Second Law of Thermodynamics

French physicist S. Carnot in 1824 realized that the efficiency of converting heat to mechanical work depended on the difference of temperature between hot and cold objects. Other scientists, such as C. Shannon and R. Landauer, have shown how the Second Law and the notion of entropy also apply to communications and information theory. In 2010, scientists from the University of Twente conducted an experiment by bouncing beads against the vanes of a windmill-like device. One side of each vane was softer than the other, and a net windmill movement occurred. Of course, the machine does not violate the Second Law—most of the beads' energy is lost through heat and sound.

1855, Bessemer Process

Ponting, C., *World History, A New Perspective*, New York: Pimlico, 2000.

1855, Cell Division

R. Remak also discovered that new cells are formed by the division of preexisting cells. F. Raspail coined the phrase *omnis cellula e cellula*.
Simmons, J., *The Scientific 100*, NY: Kensington, 1996.

1856, Plastic

Dreher, Carl, *http://tinyurl.com/k8hsxtk*.

1858, The Möbius Strip

Pickover, C., *The Möbius Strip*, Thunder's Mouth Press, 2006.

1859, Darwin's Theory of Natural Selection

Darwin, C., *The Origin of Species by Means of Natural Selection* (many editions)

Quammen, D., *The Reluctant Mr. Darwin: An Intimate Portrait of Charles Darwin and the Making of His Theory of Evolution.* New York: W.W. Norton & Company, 2007.

Ridley, M, *Evolution*. New York: Wiley-Blackwell, 2003.

1859, Ecological Interactions

Howe, H. F., *Ecological Relationships of Plants and Animals*. New York: Oxford University Press, 1988.

Schoonhoven, L. M., et al., *Insect-Plant Biology*. New York: Oxford University Press, 2006.

1859, Riemann Hypothesis

Derbyshire, J., *Prime Obsession*, NY: Plume, 2004.

1861, Cerebral Localization

In more than 95 percent of right-handed men, language and speech appear to be mediated by the brain's left hemisphere. D. Ferrier performed tests on brains from various animals to map sensory and motor areas. Other important names in the history of cerebral localization include F. du Petit, J. Jackson, and C. Wernicke.

1861, Maxwell's Equations

Mathematical theories and formulas have predicted phenomena that were only confirmed years after the theory was proposed. For example, Maxwell's Equations predicted radio waves. All four equations in the set of equations are found, with slightly different notation, in his 1861 paper "On Physical Lines of Force." Note that it is possible to extend Maxwell's equations to allow for the possibility of "magnetic charges," or magnetic monopoles, analogous to electric charges, e.g. $\nabla \cdot \mathbf{B} = 4\pi\rho_m$, where ρ_m is the density of these magnetic charges.

Crease, R., *tinyurl.com/dxstsw*.
Feynman, R., *The Feynman Lectures on Physics, Reading,* MA: Addison Wesley, 1970.

1862, Germ Theory of Disease

Pasteur's vaccinations were notable in that he created them from weakened organisms. This was not the case in E. Jenner's use of cowpox to provide cross-immunity to smallpox. Pasteur's work influenced J. Lister and his quest to reduce infections during surgeries through antiseptic methods.

1865, Antiseptics

Listerine mouthwash is named after Lister. Around 1862, the physician G. Tichenor used alcohol as an antiseptic for wounds.

Clark, F., *Med. Libr. & Hist. J.* 5:145; 1907.

1874, Cantor's Transfinite Numbers

Cantor's most important work relating to transfinite numbers spanned the years from about 1874 to 1883. He fully explored his thoughts on transfinite numbers in his best-known work *Beiträge zur Begründung der transfiniten Mengelehre*, 1895.

Cantor's first proof demonstrating that the set of all real numbers is uncountable, and that no one-to-one correspondence can exist between the real numbers and natural numbers, was formulated in 1873 and published in: J. *Reine Angew. Math.* 77:258; 1874.

Dauben, J., *Georg Cantor*, Harvard University Press, Cambridge, MA, 1979.

1876, Gibbs Free Energy

A nontechnical treatment of this (and thermo-dynamics in general) is a tall order, because sooner or later, it's going to be Math or Nothing.

American Physical Society. “J. Willard Gibbs,” www.aps.org/programs/outreach/history/historicsites/gibbs.cfm.
Set Laboratories, Inc. “Thermal Cracking,” www.setlaboratories.com/therm/tabid/107/Default.aspx.
Wikipedia, “Josiah Willard Gibbs,” in.wikipedia.org/wiki/Josiah_Willard_Gibbs.

1876, Telephone

John, R., *Network Nation,* Cambridge, MA: Harvard University Press, 2010.

1878, Enzymes

Berg, J. M., et al., *Biochemistry*. New York: W. H. Freeman, 2010.

Nelson, D. L., et al., *Lehninger Principles of Biochemistry*. New York: W.H. Freeman, 2012.

1878, Incandescent Light Bulb

Note that incandescent lights have many advantages, such as being able to operate at low voltages in flashlights.

1878, Power Grid

Energy Graph, http://*tinyurl.com/mxayh62*.

1887, Michelson-Morley Experiment

Trefil, J., *The Nature of Science*, NY: Houghton Mifflin, 2003.

1890, Steam Turbine

Encyclopedia Britannica, http://*tinyurl.com/ncrj8q7*.

1890, *The Principles of Psychology*

Menand, L., *The Metaphysical Club*. New York: Farrar, Straus, and Giroux, 2002.
Richardson, R. D., *William James: In the Maelstrom of American Modernism*. New York: Mariner, 2007.

1891, Neuron Doctrine

Shepherd, G., *Foundations of the Neuron Doctrine*, NY: Oxford University Press, 1991.

1892, Discovery of Viruses

In 1901, W. Reed and colleagues recognized the first human virus, yellow fever virus.

Adler, R., *Medical Firsts*, Hoboken, NJ: John Wiley & Sons, 2004.

1895, X-rays

In 2009, physicists turned on the world's first X-ray laser. It was capable of producing pulses of X-rays as brief as 2 millionths of a nanosecond. Prior to Röntgen's work, N. Tesla began his observations of X-rays (at that time still unknown and unnamed).

Haven, K., *100 Greatest Science Inventions of All Time*, Westport, CT: Libraries Unlimited, 2005.

1896, Proof of the Prime Number Theorem

Weisstein, E. *tinyurl.com/5puyan*.

Zagier, D., Math. *Intelligencer 0*:7;1977.

1896, Radioactivity

Hazen, R., Trefil, J., *Science Matters*, NY: Anchor, 1992.

Battersby, S., in Tallack, P., ed., *The Science Book*, London: Weidenfeld & Nicolson, 2001.

1897, Electron

AIP, *tinyurl.com/42snq*.

Sherman, J., *J. J. Thomson and the Discovery of Electrons*, Hockessin, DE: Mitchell Lane, 2005.

1899, Psychoanalysis

C. Jung, A. Adler, and S. Freud are considered to be among the principal founding fathers of modern psychology. The philosopher K. Popper argued that psychoanalysis is pseudoscience, and some studies suggest that outcomes from psychotherapy are no different from placebo controls. The first occurrence of the word *psychoanalysis* appears in 1896. Freud developed his initial ideas in *Studies of Hysteria*, cowritten with J. Breuer.

Hart, M., *The 100*, NY: Kensington, 1992.

Reef, C., *Sigmund Freud*, NY: Clarion Books, 2001.

Storr, A., *Feet of Clay*, NY: The Free Press, 1996.

1900, Hilbert's 23 Problems

Yandell, B., *Honors Class*, A. K. Peters, Ltd., Wellesley, MA, 2003.

1902, Chromosomal Theory of Inheritance

Today we know that the number of a creature’s chromosomes is quite varied —humans have 46, chimpanzees 48, horses 64, and gypsy moths 62.

1903, The Wright Brothers Airplane

National Parks Service, http://*tinyurl.com/mkkd4et*.

1903, Classical Conditioning

Todes, D., *Pavlov’s Physiology Factory: Experiment, Interpretation, Laboratory Enterprise*. Baltimore: Johns Hopkins, 2001.

1905, $E = mc^2$

Farmelo, G., *It Must Be Beautiful*, London: Granta, 2002.

Bodanis, D., $E = mc^2$, NY: Walker, 2005.

1905, Photoelectric Effect

Lamb, W., Scully, M., *Jubilee Volume in Honor of Alfred Kastler* (Paris: Presses Universitaires de France, 1969.

Kimble, J., et al., Phys. Rev. Lett. 39: 691; 1977.

1908, Internal Combustion Engine

For a video of the engine in action, see *http://tinyurl.com/q9f9wla*.

1910, Chlorination of Water

Darnall Army Medical Center, *tinyurl.com/48evjwo*.

1910, Main Sequence

A fun online applet, “Stellar Evolution and the H-R Diagram,” can be used to track the evolution of stars of different mass along and eventually off the main sequence: *tinyurl.com/b35942*.

1911, Atomic Nucleus

Rutherford conducted the gold foil experiment with H. Geiger and E. Marsden in 1909.

Gribbin, J., *Almost Everyone’s Guide to Science*, New Haven, CT: Yale University Press, 1999.

1911, Superconductivity

Baker, J., *50 Physics Ideas You Really Need to Know*, London: Quercus, 2007.

How Stuff Works, *tinyurl.com/anb2ht*.

1912, Continental Drift

Colbert, E. H., *Wandering Lands and Animals: The Story of Continental Drift and Animal Populations*, Mineola, NY: Dover Publications, 1985.

1913, Bohr Atom

In 1925, matrix mechanics (a formulation of quantum mechanics) was created by Max Born, Werner Heisenberg, and Pascual Jordan.

Goswami, A., *The Physicists' View of Nature*, Vol. 2, NY: Springer, 2002.
Trefil, J., *The Nature of Science*, NY: Houghton Mifflin, 2003.

1919, String Theory

See notes for Theory of Everything.
Atiyah, M., Nature, 438, 1081; 2005.

1920 Hydrogen Bonding

Wikipedia, "Hydrogen Bond," *en.wikipedia.org/wiki/Hydrogen_bond*.

1920, Radio Station

Nebeker, F., Dawn of the Electronic Age, Hoboken, NJ: John Wiley & Sons, *2009.*

1921, Einstein as Inspiration

Levenson, T., Discover, 25: 48; 2004.
Ferren, B., Discover, 25: 82; 2004.

1924, De Broglie Relation

Baker, J., *50 Physics Ideas You Really Need to Know*, London: Quercus, 2007.

1925, Pauli Exclusion Principle

Massimi, M., *Pauli's Exclusion Principle*, NY: Cambridge University Press, 2005.
Watson, A., *The Quantum Quark*, NY: Cambridge University Press, 2005.

1926, Schrödinger's Wave Equation

Max Born interpreted c as probability amplitude.
Miller, A., in Farmelo, G., *It Must be Beautiful*, London: Granta, 2002.
Trefil, J., *The Nature of Science*, NY: Houghton Mifflin, 2003.

1927, Complementarity Principle

Cole, K., *First You Build a Cloud*, NY: Harvest, 1999
Gilder, L., *The Age of Entanglement*, NY: Knopf, 2008.
Wheeler, J., *Physics Today*, 16: 30; 1963.

1927, Food Webs

Polis, G. A., et al., *Food Webs*. New York: Springer, 1995.

1927, Insect Dance Language

Stearcy, W. A., et al., *The Evolution of Animal Communication: Reliability and Deception in Signaling Systems*. Princeton, NJ: Princeton University Press, 2005.

1928, Dirac Equation

Wilczek, F., in Farmelo, G., *It Must Be Beautiful*, NY: Granata, 2003.
Freeman, D., in Cornwell, J., *Nature's Imagination*, NY: Oxford University Press, 1995.

1928, Penicillin

Although it was once believed that antibiotics in a natural setting are a means for bacteria or fungi to better compete with bacteria in the soil, American biochemist S. Waksman suggested that these microbial products are a "purely fortuitous phenomenon" and "accidental."

1929, Hubble's Law of Cosmic Expansion

Huchra, J., *tinyurl.com/yc2vy38*.

1931, Gödel's Theorem

Gödel demonstrated the incompleteness of the theory of *Principia Mathematica*.

Hofstadter, D., *Gödel, Escher, Bach*, NY: Basic Books, 1979.
Wang, H., *Reflections on Kurt Gödel*, MIT Press, 1990.

1932, Antimatter

In 2009, researchers detected positrons in lightning storms.
Baker, J., *50 Physics Ideas You Really Need to Know*, London: Quercus, 2007.
Kaku, M., *Visions*, NY: Oxford University Press, 1999.

1932, Neutron

During the process of beta decay of the free neutron, the free neutron becomes a proton and emits an electron and an antineutrino in the process.

Cropper, W., *Great Physicists*, NY: Oxford University Press, 2001.
Oliphant, M., Bull. Atomic Scientists, 38: 14; 1982.

1933, Dark Matter
Dark matter is also suggested by astronomical observations of the ways in which galactic clusters cause gravitational lensing of background objects.

McNamara, G., Freeman, K., *In Search of Dark Matter*. NY: Springer, 2006.

1933, Polyethylene
Walton, D., and P. Lorimer. *Polymers*. Oxford: Oxford Univ. Press, 2000.

1933, Neutron Stars
The neutrons in the neutron star are created during the crushing process when protons and electrons form neutrons.

1935, EPR Paradox
Although we have used spin in this example, other observable quantities, such as photon polarization, can be used to demonstrate the paradox.

1935, Schrödinger's Cat
Moring, G., *The Complete Idiot's Guide to Understanding Einstein*, NY: Alpha, 2004.

1937, Superfluids
Superfluidity has been achieved with two isotopes of helium, one isotope of rubidium, and one isotope of lithium. Helium-3 becomes a superfluid at a different lambda point temperature and for different reasons than helium-4. Both isotopes never turn solid at the lowest temperatures achieved (at ordinary pressures).

1938, Nuclear Magnetic Resonance
Ernst, R., Foreword to *NMR in Biological Systems*, Chary, K., Govil, G., eds., NY: Springer, 2008.

1941, Doped Silicon
Brain, M., http://*tinyurl.com/kov5tve*.

1942, Energy from the Nucleus
Weisman, A., *The World Without US*, NY: Macmillan, 2007.

1945, *Little Boy* Atomic Bomb

The second atomic bomb, the "Fat Man," was dropped three days later on Nagasaki. Fat Man made use of plutonium-239 and an implosion device—similar to the Trinity bomb tested in New Mexico. Six days after the Nagasaki bombing, Japan surrendered.

1945, Uranium Enrichment

US Nuclear Regulatory Commission, http://*tinyurl.com/opubbot*.

1947, Hologram

Gabor's hologram theories predated the availability of laser light sources.

One can create the illusion of movement in a hologram by exposing a holographic film multiple times using an object in different positions. Interestingly, a hologram film can be broken into small pieces, and the original object can still be reconstructed and seen from each small piece. The hologram is a record of the phase and amplitude information of light reflected from the object.

Kasper, J., Feller, S., *The Complete Book of Holograms*, Hoboken, NJ: John Wiley & Sons, 1987.

1947, Photosynthesis

Baillie-Gerritsen, V. "The Plant Kingdom's Sloth." *Protein Spotlight 38* (September 2003). *web.expasy.org/spotlight/back_issues/038/*.

1947, Transistor

Riordan, M., Hoddeson, L., *Crystal Fire*, NY: W.W. Norton & Company, 1998.

1948, Information Theory

Tallack, P., *The Science Book*, Weidenfield & Nicholson, 2003.

1948, Quantum Electrodynamics

The Lamb shift is a small difference in energy between two states of the hydrogen atom caused by the interaction between the electron and the vacuum. This observed shift led to renormalization theory and a modern theory of QED.

Greene, B., *The Elegant Universe*, NY: W.W. Norton & Company, 2003.
QED, Britannica, *tinyurl.com/yaf6uuu*.

1948, Randomized Controlled Trials
Comparative effectiveness research can sometimes be useful when performed using electronic medical records of large health networks.

Enkin, M., preface to *Randomized Controlled Trials*, Jadad, A., Enkin, M., Malden, MA: BMJ Books, 2007.

1949, Radiocarbon Dating
Other methods such as potassium-argon dating are employed for dating very old rocks.

Bryson, B., *A Short History of Everything*, NY: Broadway, 2003.

1950, Chess Computer
Computer chess, a film by Andrew Bujalski, provides some interesting background information: http://*tinyurl.com/k4cql25*.

1951, HeLa Cells
Skloot, R., *The Immortal Life of Henrietta Lacks*, NY: Crown, 2010.
Skloot, R., *tinyurl.com/y8h5trq*.

1952, Cellular Automata
Von Neumann, J., *Theory of Self-Reproducing Automata*, Urbana: IL: U. Illinois Press, 1966.
Wolfram, S., *A New Kind of Science*, Champaign, IL: Wolfram Media, 2002.

1952, Miller-Urey Experiment
The original Miller-Urey experiment's idea of a primitive atmosphere was probably wrong, but complex biochemicals can be formed under many other conditions. This takes us right into origin-of-life books, which are many and various (and often contain political or religious/antireligious agendas of their own).

1953, DNA Structure
DNA may be used to assess hereditary risk for certain diseases. Gene therapy, in which healthy genes are inserted into human cells, continues to be researched for treatment of diseases. Understanding gene regulation, in which genes become active and inactive, is crucial to our understanding of DNA function.

Ridley, M., jacket flap for *DNA*, Krude, T., ed., NY: Cambridge University

Press, 2004.

1955, Atomic Clocks

In 2010, "optical clocks" that employ atoms (e.g. aluminum-27) that oscillate at the frequencies of light rather than in the microwave range were among the most precise timekeepers.

1955, Birth-Control Pill

The mini-pill was introduced in the early 1970s, and it contained only progestin. It prevented pregnancy solely through changes in the cervix and uterus. Other key scientists in the development of the pill are J. Rock and M. C. Chang.

1955, Placebo Effect

Placebo treatments of gastric ulcers have often been as effective as acid-secretion inhibitor drugs, as confirmed by stomach endoscopy. Many recent clinical trials of antidepressant medications have shown that sugar pills can provide the same relief.

Shapiro, A., Shapiro, E., in *The Placebo Effect*, Harrington, A., ed., Cambridge, MA: Harvard University Press, 1999.

1955, Ribosomes

Garrett, R. A., et al., (eds.), *The Ribosome: Structure, Function, Antibiotics, and Cellular Interactions*. Washington, DC: American Society Microbiology 2000.

1957, Antidepressant Medications

Healy, D., *The Anti-Depressant Era*. Cambridge, MA: Harvard University Press, 1999.

1957, Space Satellite

Jorden, W., http://*tinyurl.com/lc6rm6s*.

1958, Central Dogma of Molecular Biology

Ridley, M., *Francis Crick: Discoverer of the Genetic Code*. New York: Eminent Lives, 2006.

1958, Integrated Circuit

Bellis, M., *tinyurl.com/y93fp7u*.
Miller, M., *tinyurl.com/nab2ch*.

1959, Structure of Antibodies

Monoclonal antibodies, derived from a single immune cell, have been found that recognize certain human cancers.

1960, Laser

Hecht, J., *Understanding Lasers*, Piscataway, NJ: IEEE Press, 2008.

1961, Cracking the Genetic Code for Protein Biosynthesis

Alberts, B., et al., *Molecular Biology of the Cell*. New York: Garland Science, 2007.

1961, First Humans in Space

In honor of Yuri Gagarin's status as the first person to travel into space, every April 12 since 2001 has been celebrated as "Yuri's Night" at space-related parties and events around the world. Find out more about the next Yuri's Night at *yurisnight.net*.

1961, Green Revolution

Jain, H., *The Green Revolution*, Houston, TX: Studium, 2010.

1961, Standard Model

S. Glashow's discovery of a way to combine the electromagnetic and weak interactions (the latter of which is also referred to as weak nuclear force) provided one of the earlier steps toward the Standard Model. Other key individuals include S. Weinberg and A. Salam.

While on the subject of subatomic particles, note that in 1935, Hideki Yukawa predicted the existence of the meson (later called the pion) as a carrier of the strong nuclear force that binds atomic nuclei. Gluons are involved in interactions among quarks, and are indirectly involved with the binding of protons and neutrons.

Battersby, S., in Tallack, P., ed., *The Science Book*, London: Weidenfeld & Nicolson, 2001.

1963, Chaos and the Butterfly Effect

Gleick, J., *Chaos*, NY: Penguin, 1988.
Lorenz, E., J. Atmos. *Sci*. 20:130;1963.

1963, Cognitive Behavioral Therapy

Mathematician J. Nash is famous for claiming that he was able to overcome his schizophrenia to a large degree by a reasoning process in which he was able to persuade himself of the improbability of the conclusions he was making. By adjusting his thinking about his delusions and the voices he heard, he was able to diminish their hold over him.

1964, Brain Lateralization

Schwartz, J. M., et al., *The Mind and the Brain: Neuroplasticity and the Power of Mental Force*. New York: Regan Books, 2003.

1964, Quarks

Jones, J., Wilson, W., *An Incomplete Education*, NY: Ballantine, 1995.

1965, Cosmic Microwave Background

In 1965, R. Dicke, P. J. E. Peebles, P. G. Roll, and D. T. Wilkinson interpreted the results of A. Penzias and R. Wilson and declared the background radiation as a signature of the big bang. The WMAP satellite, launched in 2001, provided additional detail on these fluctuations. The HIGH-altitude BOOMERANG balloon, flown over Antarctica in 1997, 1998, and 2003, also provided observations of the CMB.

Bryson, B., *A Short History of Everything*, NY: Broadway, 2003.

1966, Dynamic RAM

Wang, D., http://*tinyurl.com/kjp5th7*.

1967, Endosymbiont Theory

Kozo-Polyansky, B. M., et al., *Symbiogenesis: A New Principle of Evolution*. Cambridge, MA: Harvard University Press, 2010.

1967, Heart Transplant

Fitzpatrick, L., *tinyurl.com/ylrlnmp*.

1967, Saturn V Rocket

Tate, K., http://*tinyurl.com/afo3foz*.

1969, ARPANET

Stewart, W., http://*tinyurl.com/dd4mzc*.

1969, First on the Moon

Apollo Lunar Surface Journal: *tinyurl.com/2bmqcq*.

1972, Genetic Engineering

Voosen, P., http://*tinyurl.com/l7a4edl*.

1975, Feigenbaum Constant

Feigenbaum, M., “Computer Generated Physics,” in *20th Century Physics*, Brown, L. et al., eds., NY: AIP Press, 1995.

May, R., *Nature* 261:459;1976.

1975, Fractals

Many visually interesting fractals are generated using iterative methods that were first introduced by mathematicians G. Julia and P. Fatou from 1918 to 1920.

Mandelbrot, B., *The Fractal Geometry of Nature*, W. H. Freeman, NY, 1982.

1977, Public-Key Cryptography

Diffie, W., Hellman, M., *IEEE Trans. Info. Theory* 22:644;1976.

Hellman, M., *Sci. Am.* 241:146;1979.

Lerner, K., Lerner, B., eds., *Encyclopedia of Espionage Intelligence and Security*, Farmington Hills, MI, Gale Group, 2004.

Rivest, R., Shamir, A., Adleman, L., *Commun. ACM* 21:120;1978.

1978, Theory of Mind

Tomasello, M., *The Cultural Origins of Human Cognition*. Cambridge, Harvard University Press, 1999.

1979, Gravitational Lensing

Wikipedia’s “Gravitational lens” page at *tinyurl.com/ola3h* contains visualizations and animations that further explain the concept.

1980, Cosmic Inflation

Other contributors to inflation theory are P. Steinhardt and A. Albrecht. Inflationary theory suggests why magnetic monopoles have not been discovered. Monopoles may have formed in the Big Bang and then dispersed during the inflationary period, decreasing their density to such an extent as to make them undetectable.

Guth, A., *The Inflationary Universe*, NY: Perseus, 1997.

Musser, G., *The Complete Idiot’s Guide to String Theory*, NY: Alpha, 2008.

1981, Quantum Computers

Other important names associated with quantum computing include C.

Bennett, G. Brassard, and P. Shor.

Clegg, B., *The God Effect*, NY: St. Martins, 2006.
Kaku, M., *Visions*, NY: Oxford University Press, 1999.
Kurzweil, R., The Singularity is Near, NY: Viking, 2005.
Nielsen M., Chuang, I., *Quantum Computation and Quantum Information*, NY: Cambridge University Press, 2000.

1982, Artificial Heart

Long, T., http://*tinyurl.com/kjqjd3m*.

1984, Telomerase

Telomerase is a reverse transcriptase that creates single-stranded DNA from single-stranded RNA as a template. J. Szostak was also involved in the discovery of telomerase. Shortened telomeres have been associated with Alzheimer's disease, cardiovascular disease, diabetes, cancer, childhood trauma, and prolonged depression.

Greider, C., Blackburn, E., *Scien. Amer.* 274:92; 1996.

1984, Theory of Everything

Note that in modern quantum theories, forces result from the exchange of particles. For example, an exchange of photons between two electrons generates the electromagnetic force. At the Big Bang, it was thought that all four forces were really just one force, and only as the universe cooled did the four forces become distinct.

Greene, B., *The Elegant Universe*, NY: W.W. Norton & Company, 2003.
Kaku, M., *Visions*, NY: Oxford University Press, 1999.
Lederman, L., Teresi, D., *The God Particle* (Boston, MA: Mariner, 2006).

1987, Mitochondrial Eve

Sykes, B., *The Seven Daughters of Eve: The Science That Reveals Our Genetic Ancestry*. New York: W.W. Norton & Company, 2002.

1990, Domains of Life

Margulis, L., et al., *Kingdoms and Domains: An iIllustrated Guide to the Phyla of Life on Earth*. New York: Academic Press, 2009.

1990, World Wide Web

Hafner, K., *Where Wizards Stay Up Late*, New York: Simon & Schuster,

1998.

1994, Global Positioning System (GPS)

Lagunilla, J., Samper, J., Perez, R., GPS and Galileo, New York: McGraw-Hill, 2008.

1998, Dark Energy

Overbye, D., http://*tinyurl.com/y99ls7r*.

Tyson, N., *The Best American Science Writing 2004*, D. Sobel, ed., NY: Ecco, 2004.

Tyson, N., Goldsmith, D., *Origins*, NY: W.W. Norton and Company, 2005.

1998, International Space Station

An animation showing the assembly sequence for the ISS between 1998 and 2011 can be found at *tinyurl.com/d4plha*.

2003, Human Genome Project

Donovan, A., Green, R., *The Human Genome Project in College Curriculum*, Lebanon, NH: Dartmouth, 2008.

2004, *Spirit* and *Opportunity* on Mars

Jim Bell's coffee table book *Postcards from Mars* (New York: Dutton, 2006) and his stereo-viewer book *Mars 3-D* (New York: Sterling, 2008) showcase the stories and photographic highlights from the *Spirit* and *Opportunity* rover missions.

2008, Human Cloning

In reproductive cloning, the clone is not truly identical since the somatic (body) cell may contain mutations in the DNA, as well as specific methylation patterns. Also, the mitochondrial DNA comes from the donor egg. Note also that the environments in the uterus and in the egg play a role in the development of an embryo and shape some of its characteristics. In plants, clones can be made simply by cuttings of plants. Some variety of grapes used today for making wine are clones of grapes that first appeared 2,000 years ago. For research purposes, cloning can be used to create animals with the same genetic blueprint and thus eliminate many variables during experiments. Areas for possible use include the treatment of Alzheimer's, Parkinson's, and other degenerative diseases.

Researchers have made iPS cells from blood and skin and then induced these iPS cells into becoming heart muscles and brain and spinal-cord neurons. Such cells might be used to replace damaged heart tissue. Perhaps by cloning healthy heart cells and injecting them into damaged regions of the heart, certain kinds of heart disease can be ameliorated.

After SCNT, the nucleus-egg combination is stimulated with electricity to trigger cell division.

Bailey, R., foreword to Gralla, J., Gralla, P., *Complete Idiot's Guide to Understanding Cloning*, NY: Alpha, 2004.

2009, Large Hadron Collider

The LHC is a synchrotron accelerator.

Bryson, B., *https://tinyurl.com/yasm4y2x*..

2016, Gravitational Waves

A great collection of free *Scientific American* articles about the discovery of gravitational waves can be found online at: *tinyurl.com/yb2xwrvs*.

2017, Proof of the Kepler Conjecture

Donev, A. et al. *Science*, 303;990;2004.
Hales, T. *Ann. Math*. 162:1065;2005.
Spizo, G. *Kepler's Conjecture*, John Wiley & Sons, 2003.

About the Contributors

Jim Bell, PhD, author of *The Space Book*, is a professor at Arizona State University's School of Earth and Space Exploration in Tempe, Arizona, and an adjunct professor in the Department of Astronomy at Cornell University in Ithaca, New York. As President of The Planetary Society, he is an active and prolific public commentator on science and space exploration, earning the 2011 Carl Sagan Medal from the American Astronomical Society. Bell has appeared on numerous radio and television shows, including the NBC *Today Show* and PBS *News Hour,* as well as programs on the Discovery, National Geographic, and History channels. Author of six books, he has been involved in such NASA robotic exploration missions as the Near Earth Asteroid Rendezvous (NEAR), Mars Pathfinder, the Mars rovers *Spirit, Opportunity,* and *Curiosity*, and the Lunar Reconnaissance Orbiter. The main belt asteroid 8146 Jimbell is named in his honor.

Marshall Brain, author of *The Engineering Book*, is best known as the founder of HowStuffWorks.com, and is the bestselling author of the How Stuff Works series (Wiley). He has appeared on *Oprah*, *Dr. Oz, Good Morning America*, CNN, *Modern Marvels,* and in many other media outlets to apply his signature approach to unraveling the mysteries of life. He is also the host of the National Geographic Channel's *Factory Floor with Marshall Brain* TV show. He lives in Cary, North Carolina.

Michael C. Gerald, PhD, author of *The Biology Book*, was Professor Emeritus of Pharmacy at the University of Connecticut and served as dean of the school. He was previously a professor of pharmacology and associate dean at the College of Pharmacy at The Ohio State University and a consultant to the World Health Organization in Geneva. A past member of the Board of Directors of the Patient Access Network Foundation, he authored more than 100 publications and six books, including *The Drug Book* (Sterling), *The Poisonous Pen of Agatha Christie* (University of Texas Press), and *The Complete Idiot's Guide to Prescription Drugs* (Alpha). He resided with his wife and collaborator, Gloria, in Storrs Mansfield, CT.

Derek B. Lowe, author of *The Chemistry Book*, has worked for several major pharmaceutical companies on drug discovery projects against schizophrenia, Alzheimer's, diabetes, cancer, and other diseases. After receiving his PhD in chemistry from Duke University, he was awarded a Humboldt fellowship to do postdoctoral research in Germany and has since handled at least 58 elements of the periodic table as part of his research. His columns on organic and medicinal chemistry are featured in the Royal Society of Chemistry journal *Chemistry World*, and he has served on the advisory board for *Chemical & Engineering News*. Having written daily for the popular *In the Pipeline* blog (blogs.sciencemag.org/pipeline) for over 16 years, Lowe is also a science blog pioneer with 14,000 Twitter followers. He lives in Massachusetts.

Clifford Pickover, author of *The Math Book, The Physics Book,* and *The Medical Book,* is a prolific author, having published more than fifty books, translated into over a dozen languages, on topics ranging from science and mathematics to religion, art, and history. He received his PhD from Yale University and has been granted more than 500 US patents. He has also been elected a Fellow for the Committee for Skeptical Inquiry for "significant contributions to the general public's understanding of science, reason, and critical inquiry through scholarship, writing, and work in the media." His research has received considerable attention from media outlets ranging from CNN and *WIRED* to *The New York Times*, and his website, www.pickover.com, has received millions of visits. Pickover has also cultivated an extensive social media presence, exposing a large audience to innovation and creative thinking, with more than 30,000 Twitter followers and 3 million tweet-views a month. *The Math Book* won the Neumann Prize, awarded every two years for the best book in the history of mathematics aimed at a broad audience.

Wade E. Pickren, author of *The Psychology Book*, received his PhD in Psychology and the History of Science from the University of Florida. He served as the Historian of the American Psychological Association from 1998 to 2012 and also as the Editor of the APA journal, *History of Psychology*. Pickren has served as President of the Society for the History of Psychology and also served as President of the Society for General Psychology. Additionally, he is the Editor-in-Chief of the *Oxford Research Encyclopedia of the History of Psychology* and the forthcoming *Cambridge Handbook of the Intellectual History of Psychology*. His current writing project is a history of psychology and health for Routledge. Pickren has given talks and workshops on four continents and is author/editor of eight books. He recently retired from a position in higher education and now devotes his time to writing and gardening.

Photo Credits

Because several of the old and rare illustrations shown in this book were difficult to acquire in a clean and legible form, I have sometimes taken the liberty to apply image-processing techniques to remove dirt and scratches, enhance faded portions, and occasionally add a slight coloration to a black-and-white figure in order to highlight details or to make an image more compelling to look at. I hope that historical purists will forgive these slight artistic touches and understand that my goal was to create an attractive book that is aesthetically interesting and alluring to a wide audience. My love for the incredible depth and diversity of topics in science and history should be evident through the photographs and drawings.

© **Allegheny Observatory Records, 1850-1967, UA.5.1, University Archives, Archives & Special Collections, University of Pittsburgh Library System:** 91

Bridgeman Images: 73

British Library: 51

CERN: 505

Courtesy of Brookhaven National Laboratory: 303, 345, 347, 435, 443, 483

Dreamstime: © Damirfajic: 447

Eric Erbe/USDA, ARS, EMU: 125

ESO: 299

Flickr: Liz West: 417

© **Fractal Art by G. Fowler:** 153

Getty Images: © Bettmann: 151; © Yvonne Hemsey: 395; © Ira Wyman/Sygma: 475

© **George W. Hart, http://www.georgehart.com:** 108

Joan O'Connell Hedman: 111

Courtesy of HEIST: 249

Institute of Biblical & Scientific Studies: 23

iStock: © -M-I-S-H-A-: 69; © chinaface: 39; © Gannet77: 141; © ihoe: 99; © Charles Mann: 195; © Christian Riedel: 481: © silkfactory: 31; © SMWalker: 29; © styf22: 199; © theasis: 163; © Trout55: 315

© Roger A. Johnston, Fractal image created with Apophysis (software available at www.apophysis.org): 437

Lawrence Berkeley National Lab: 495

© Jos Leys (josleys.com): 89, 183, 463

© Teja Krasek, http://tejakrasek.tripod.com: 148

Library of Congress: 17, 117, 155, 159, 197, 213, 221, 285, 295, 317

© Robert Lord: 465

© Tibor Maljath: 227

© Oskar Morgenstern, photographer. From the Shelby White and Leon Levy Archives Center, Institute of Advanced Study, Princeton, NJ, USA: 343

NASA: 251, 353, 403, 419, 445, 453, 456, 457, 489, 509; ESA, Richard Ellis (Caltech) and Jean-Paul Kneib (Observatoire Midi-Pyrenees, France): 469; JPL: 119; JPL-Caltech/T. Pyle (SSC/Caltech): 129; JPL/Cornell/USGS: 500, 501; STS-119 Shuttle Crew: 497; Swift Science Team/Stefan Immler: 349; WMAP Science Team: 471

National Archives: 193

National Institutes of Health: 145, 399; NLM: 389; Rocky Mountain Laboratories, NIAID: 233

National Institute of Standards and Technology: 407; J. Jost: 473

© Paul Nylander, bugman123.com: 49

Perry Point VA Hospital, Perry Point, MD: 286

© Clifford A. Pickover: 80, 81, 109, 143, 387

© Clifford A. Pickover and Teja Karasek: 219

Courtesy of Wade E. Pickren: **263**

Private collection: 37, 43, 57, 79, 83, 107, 135, 139, 147, 181, 189, 207, 210, 243, 281, 289, 319, 327, 333, 337, 341, 368, 383

Royal Belgian Institute of Natural Sciences: 13

Science Museum: 95

Shutterstock: © -baltik: 355; © 1236997115: 309; © Allison Achauer: 253; © ajt: 411; © albund: 441; © Alegria: 323; © Hintau Aliaksei: 64; © Alila Medial Media: 421; © Anneka: 179; © anotherlook: 177; © Yuri Arcurs, 2010: 167; © ARENA Creative: 491; © ArtisticPhoto: 255; © Awe Inspiring Images: 127; © Jim Barber: 201; © beboy: 279; © concept: 241; © Luis Francisco Cordero: 203; © CURAphotography: 451; © Mikael Damkier: 27; © Andreas Danti: 149; © Soren Egeberg: 223; ©Ekapong: 21; © Ella, 2009: 75; © EML: 325; © Jonathan Esper: 235; © Lisa Fischer: 409; © garloon: 332; © Christos Georghiou: 93; © Tom Grundy: 77; © Andreas Guskos, 2009: 59; © Patrick Hoff: 293; © hxdbzxy: 217: © immelstorm: 304; © iophoto: 205; © Ivan Cholakov Gostock-dot-net: 313; © Eugene Ivanov: 329; © Jessmine: 257; © Jhaz Photography: 275; © Wayne Johnson, 2009: 385; © jps: 449; © Judex: 439; © JustASC: 393; © karinkamon: 433; © Sebastian Kaulitzki: 101, 122, 123, 361, 425, 477; © kazoka: 307; © Knorre: 215, 282; © Oleg Kozlov: 173; © Renjith Krishnan: 265; © lculig: 283; © lebanmax: 61; © Wong Yu Liang: 15; © Luis Louro: 351; © Sandy MacKenzie: 415; © Sandro V. Maduell: 423; © Marioner: 381; © Mark R.: 311; © mathagraphics: 267; © John R. McNair: 231; © Christopher Meade: 339; © Andreas Meyer: 53; © mikeledray: 479; © Olga Miltsova: 357; © MNStudio: 467; © molekuul_be: 305; © Monkey Business Images: 503; © Mopic: 405; © MWaits, 2009: 133; © mylifeiscamp: 19; © Chepe Nicoli: 301; © Mike Norton: 90; © photoBeard: 397; © Kenneth V. Pilon: 175; © Albert Russ: 247; © Shchipkova Elena: 225; © Scubaluna: 331; © Hisom Silviu, 2009: 55; © slava17: 191; © Carolina K. Smith, M.D.: 365; © sspopov: 367; © Maree Stachel-Williamson, 2010: 511; © STILLFX: 157, 410; © Ronald Sumners: 171; © SunnyS: 239; © sursad: 209; © Tefi: 185; © Tischenko Irina: 65, 211; © Lee Torrens: 269; © Vladimir Wrangel: 391; © YAKOBCHUKVASYL: 121, 229; © yanqiu: 25; © Yare Marketing: 271; © Yellowj: 245; © ynse: 165; © Juan Carlos Zamora: 296; © zebra0209: 35

Courtesy of The Swiss Post, Stamps & Philately: 131

Thinkstock: © Robert Corse: 493

U.S. Army/Spc. Michael J. MacLeod: 291

© **Steven Whitney at 25yearsofprogramming.com:** 461

© **Rien van de Weigaert, www.astro.rug.nl/~weygaert:** 63

© **Robert Webb using Stella4D software, http://www.software3d.com:** 259

Courtesy of Wikimedia Foundation: 47, 71, 103, 110, 113, 161, 164, 170, 172, 174, 196, 230, 244, 264, 278, 321; Abgent/Kosi Gramatikoff/Edited by Seth Miller: 429; The Air Force Research Laboratory's Directed Energy Directorate: 427; Apple2000: 335; Armand69: 67; Avenue: 237; Clement Bardot: 487; FastLizard4: 455; Steven Fruitsmaak: 45; Fvoigtsh: 413; Eric Gaba/derivative work by Matthew Stevens: 187; Google cultural Institute: 485; Houghton Library: 262; Robert Huffstutter: 277; Ricardo Liberato: 33; © 2005 Richard Ling: 401; Heike Lochel: 379; NARA: 371; NASA: 377; Orientalist: 297; Osborne House, Isle of Wight: 507; Heinrich Pniok: 273; Sage Ross: 85; Stefan scheer (photographer)/Stefanie Krull, Neanderthal Museum: 499; Siemens AG Pressbilder/Presspictures: 261; Softeis: 105; Ryan Somma: 41; Tekashifuka: 287; Carsten Ullrigh: 169; University of Toronto, Wenceslas Hollar Digital Collection: 97; U.S. Army Photo: 375; U.S. Army/Ed Westcott: 369; U.S. DOE: 373; Uppsala University: 137; Wel. come Collection: 87, 188; www.glofish.com: 459; Tom Yates: 359

Yale University/Beinecke Rare Book and Manuscript Library: 246