The Endless Pathways of Discovery

Floyd E. Bloom

Last month, *Science* selected the opportunities presented by research on embryonic stem cells as the latest of our Breakthroughs of the Year (*Science*, 17 December 1999, pp. 2238 and 2267). That discovery, like all scientific research, was possible only because of the previously accumulated body of scientific information, hypotheses, and tools of observation. Our annual selections of Breakthroughs are intended to draw attention to significant scientific achievement. But knowing that any annual retrospective is both temporally and substantively shortsighted, *Science* begins with this issue a "Pathways of Discovery" series as part of our yearlong special coverage of the transition into the next millennium.

For the remainder of 2000, the second issue of each month will include an essay portraying the pathways of discovery in exciting areas of investigation ranging from quantum physics to cosmology and from genomics to atmospheric sciences. For each topic covered, all of them coordinated by Contributing Editor Ivan Amato, distinguished scientists will review what they see as the major past heuristic accomplishments along the intellectual pathway they presently traverse, and they'll imagine the downstream terrain of that pathway through extrapolation from discoveries unfolding now.

The opening essay of this series, by Stephen Jay Gould (p. 253), is a provocative approach to the question of what distinguishes the scientific way of knowing about the world and what it is about that way of knowing that is all too human. Gould sees a false dichotomy in today's "science wars" between scientist-realists and humanist-relativists who question whether scientific truth has any special standing among other claims of truth. His assessments will prepare readers of subsequent essays for the mix of rational and nonrational influences that continually shape the ever more-revealing worldview scientists have been building.

"*Science* begins with this issue a 'Pathways of Discovery' series..."

To help lay out our year of Pathways essays, in this issue we have assembled a graphical timeline of major past events and agents of discovery. The points along the way were drawn from initial selections by *Science*'s editors and then refined and vetted with the help of historians of science (the editors retain credit for any errors, omissions, or overemphases). From this overarching timeline of discovery, an at least arguable origin for each of the 11 essay topics to follow can be seen (p. 230). Each essay will include a more focused timeline depicting pathways of discoveries germane to the topic. In addition, through collaboration with the *Encyclopedia Britannica*, their Web site (www.britannica.com) will enrich each month's essay with links to unique historical and other informational resources.

These timelines serve as convenient simplifications of the spectacular and progressive accumulation of insight and understanding scientists have achieved. A more detailed visual metaphor of this progress would look like an intricate circulatory system with multiple ever-finer branchings that often interconnect with other parts of the nexus. Science has indeed become a process of continuous specialization, yet each new capillary of investigation contributes to the overall understanding. As some of our essays will show, like that on genomics by Eric Lander and Robert Weinberg slated for March, each new branch of science can open wondrous new opportunities while posing societal challenges that will require vigilance and insightful management.

The unavoidable consequence of focusing on the pathways we have chosen to highlight in this series is the obligatory omission of the many, many other important pathways of discovery that deserved equal recognition in our homage to the past. Recognizing that a truly comprehensive portrayal of science's leading edges was beyond our resources, we opted for some themes that have figured prominently in our pages over the past decade as examples of the flows of ideas and technologies within and between the various pathways of science.

For this editor, the most remarkable conclusion to emerge from this exercise was the realization* that in the millennium we are about to leave, humanity's knowledge of its place in the universe has moved from St. Thomas Aquinas's view that knowledge was of two types—that which man could know and that which was "higher than man's knowledge" and not to be sought through reason—to the belief begun with Newton's *Principia* that our universe and all within it are indeed knowable. We eagerly await readers' views of our Pathways.

*A. Lightman, *New York Times Magazine*, 19 September 1999, p. 94.

pathways of discovery

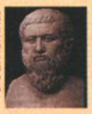
To help readers negotiate *Science* magazine's yearlong series, Pathways of Discovery, we compiled this timeline. It leaves out far more than it includes, but we hope it—along with Stephen Jay Gould's provocative essay on page 253 and this issue's editorial by *Science* Editor-in-Chief Floyd Bloom—will give readers an idea of what to expect from this series. A schedule of the essay topics appears in the upper right of the graphic.

Prior to 600 B.C.
Prescientific Era
Phenomena explained within contexts of magic, religion, and experience.

6th Century B.C.
Greek philosophers begin constructing natural and rational explanations for phenomena.

582–500 B.C.
Pythagoras
Recognizes connection between mathematics and nature.
"All is number."

5th to 4th Centuries B.C.
Leucippus and Democritus
Articulate the earliest known version of atomism.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427–347 B.C.
Plato
Emphasizes the value of theory.


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384–322 B.C.
Aristotle
Supports logic and common sense in the observation and classification of natural phenomena. His writings become a cornerstone of Western thinking for nearly 2000 years.

Birth of alchemy


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3rd to 2nd Centuries B.C.
Euclid
Writes *The Elements*, one of the earliest logically built texts using axioms and logical deduction for geometric proofs.

287–212 B.C.
Archimedes
Recognizes how theory can lead to technological insight.

B.C. A.D.

140
Ptolemy
Summarizes his geocentric astronomy, which reigns until Copernicus (1543).

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131–200
Galen
Writes text on anatomy that is preeminent until Vesalius (1543).

500
Symbol for "zero" created in India
"0"

1000
Mayan and Hindu skywatchers make astronomical observations for agricultural and religious purposes.

1166
Oxford University is founded and becomes model for other European universities.

13th Century
Mechanical clocks proliferate

1285–1349
William of Ockham
Touts simplicity in explanation as a virtue.

1370
Synchronization of clocks in Paris, an emblematic moment in the history of standardization.

1454
Johannes Gutenberg
Demonstrates movable type printing press in Germany.


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1454
Paracelsus
His anti-authoritarianism helps West break loose from scholastic dogma.

1500s

1543
Andreas Vesalius
Publishes *De Corpus Humani Fabrica*, displacing Galen as the authority on anatomy.


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1543
Nicolaus Copernicus
Publishes *De Revolutionibus Orbium Coelestium*, displacing geocentric (Ptolemaic) system with heliocentric system.

1570
Tycho Brahe
Increases accuracy of astronomical observation.

1590
Zacharias Janssen
Builds first microscope.

1600s

1600
William Gilbert
Publishes *De Magnete*, in which he postulates that Earth behaves as a huge magnet.

1608
Hans Lippershey
Manufactures first telescopes; originally used for military purposes.

1609
Johannes Kepler
Publishes *Astronomia Nova*, in which he defines first two laws of planetary motion.


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2
1610
Galileo Galilei
With one of the first telescopes, he makes extensive astronomical observations; publishes *Siderus Nuncius*.

1620
Francis Bacon
Publishes *Novum Organum*, in which he espouses careful observation and inductive reasoning as a basis of scientific study.
"I have taken all knowledge to be my province."

1629
William Harvey
Publishes *De Motu Cortus et Sanguinis*, by which he establishes the basic geometry of the circulatory system.

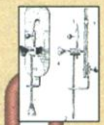

MARK MARTEN/NLM/PHOTO RESEARCHERS

1637
René Descartes
His *Discours de la Methode* combines skepticism, algebra, and geometry into the powerful mathematical method of analysis.

10
1643
Evangelista Torricelli
Invents the barometer.
"We live submerged at the bottom of an ocean of the element air."

1660
Royal Society in England is legally chartered.

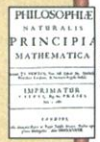
1661
Robert Boyle
Publishes *The Skeptical Chymist*, helping to establish a more modern basis for chemistry.



1676
Anton van Leeuwenhoek
Uses simple microscope to magnify world up to 200 times. In pond water, he sees tiny living organisms. A pathway to microbiology opens.

1686
John Ray
Starts publishing a three-volume classification of 18,600 different plant species.

1687
Isaac Newton
Publishes his *Principia Mathematica*, in which he lays out mathematically the laws of motion, universal gravitation, and the scientific method in general.



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1700s

1705
Edmund Halley
Predicts that a comet will return in 1758. When it does, it serves as a powerful demonstration of science's ability to understand the world.

1714
Daniel Fahrenheit
Invents mercury thermometer and standardizes it with ice and boiling water.

1720
Lady Mary Wortley Montagu
Introduces early technique of immunization.

1735
Carolus Linnaeus
Publishes *Systema Natura*, thereby greatly pushing forward systematic study and rules of classification of living kingdom.

1750
Benjamin Franklin
Shows lightning to be an electrical discharge.


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1758
Halley's Comet returns

1759
Kaspar Wolff
Shows that specialized organs develop out of unspecialized tissue, a pathway to developmental biology.


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1769
Antoine Lavoisier
Raises practice of making quantitative measurement in chemical studies to a level that earns him eternal credit as the father of modern chemistry.

All-Too-Human Science

Pathways of discovery are only smooth and linear when the nuanced and tortuous history of science is brutally edited to fit into a finite space. The items to the right represent the countless twists, turns, ironies, contradictions, tragedies, and other unkempt historical details that have synthesized into the far more complex and multitextured reality of the scientific adventure.

4th century B.C.: Aristotle rejects the atomism of Leucippus and Democritus in favor of the four-element material system—earth, air, fire, and water. Atomism doesn't surface seriously for 2000 years. Meanwhile, the four-element philosophy spurs alchemical thought and practice. The power of authority often still poses obstacles to new ideas.

9th to 15th centuries: The flow of science and technology is mostly *into* Europe *from* Islam and China. Among the innovations diffusing westward: paper, chemical technology, glassmaking, the compass, shipbuilding, and gunpowder. In the 15th century, the centers of science and technology begin shifting to the West.

1543: Copernicus helps begin the scientific revolution with his heliocentric theory of the universe. Yet he retains the perfect circularity of orbits demanded by Platonic idealism and Ptolemaic astronomy. His work embodies both a radicalism that unlocks new knowledge and a conservatism. These together account for much of the progressive nature of scientific knowledge.

1633: The Holy Inquisition threatens Galileo Galilei with torture unless he renounces heliocentrism. He acquiesces but is confined to house arrest for the rest of his life for previously defying Church authority by publicly promoting the theory. The Galileo affair has since represented—in the most dramatic fashion—the tension between scientific and religious authority.

17th century: Even as Isaac Newton ascends to become an icon of the scientific revolution, he devotes 1 million words and countless hours of his intellect to the practice of alchemy. The ability of the human mind to simultaneously entertain contrary belief systems is a perennial source of wonder.

c1900: Shortly after Röntgen discovered x-rays, the French physicist, René Blondlot, claimed discovery of what he called "N-rays." Other scientists confirmed his observations. Papers were published. Trouble was, N-rays didn't exist. This episode has become a classic case of "pathological science" in which self-deception, wishful thinking, and selective use and negligence of data can lead scientists astray.


AMERICAN INSTITUTE OF PHYSICS

PATHWAY TO ...

1	"Science Wars"	January	7	Communications	July
2	Planetary Sciences	February	8	Quantum Physics	August
3	Genomics	March	9	The Cell Cycle	September
4	Infectious Diseases	April	10	Atmospheric Sciences	October
5	Materials Science	May	11	Neuroscience	November
6	Cloning/Stem Cells	June	12	Astrophysics/ Cosmology	December

Along the timeline, colored numbers and arrows mark points of departure. These are moments in the history of science where the pathways of discovery associated with each of the 11 topical essays in the series might have begun to unfold.

1780
Luigi Galvani
Observes connection between electricity and muscle action.

... kilometer, meter, millimeter ...

1785
James Hutton
Publishes *Theory of Earth*, arguing for a picture of gradual, steady terrestrial changes that became known as uniformitarianism.

1790
Metric system developed

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4

1796
Edward Jenner
Develops technique he called vaccination; the science of immunology begins.

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1798
Georges Cuvier
Publishes first work of comparative anatomy that would support the later evolutionists; his later work with fossils would found the field of paleontology.

1800s

1806
Alessandro Volta
Invents the electric battery, thereby opening the way to several new sciences—including electrochemistry—and technologies.

1808
John Dalton
Publishes *New System of Chemical Philosophy*, refining idea of atoms and how they combine.

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1809
Jean-Baptiste de Lamarck
Publishes *Zoological Philosophy*, in which he proposes that evolution occurs by the inheritance of traits acquired during lifetime.

1820
Hans Christian Oersted
Discovers connection between electricity and magnetism, that is, the basic principle of electromagnetism.

1828
Friedrich Wöhler
Synthesizes an organic compound, urea, in the laboratory, thereby breaking down categorical distinction between life and nonlife.

1830
Charles Lyell
Publishes first volume of *The Principles of Geology*.

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1837
Louis Agassiz
Argues for the existence of an ice age in the past.

9

1838–39
Matthias Schleiden and Theodor Schwann
Develop cell theory—that living things are made of cells.
"The elementary parts of all tissues are formed of cells in an analogous, though very diversified manner, so that it may be asserted that there is one universal principle of development for the elementary parts of organisms, however different, and that this principle is the formation of cells."

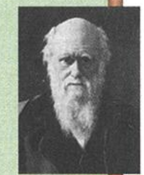
1840
James Joule
Develops the concept of conservation of energy.

7

1844
First electric telegraph

1856
William Ferrel
Publishes *Essay on the Winds and Currents of the Ocean*, a pivotal work in history of meteorology.

1859
Charles Darwin
Publishes *The Origin of Species*.



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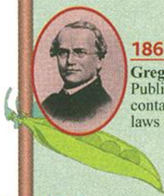
1865
Gregor Mendel
Publishes work containing his famous laws of heredity.



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1860s
Henry Sorby
Emphasizes how material properties depend upon their internal microscopic structure.

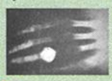
1869
Dmitri Mendeleev
Publishes his Periodic Table of the Chemical Elements.

11

1889
Camillo Golgi
Uses techniques to lay bare the cellular anatomy of the brain.

K. SUTLIFF

1895
Wilhelm Röntgen
Discovers x-rays.



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1897
Marie Curie
She and husband Pierre clarify concept of radioactivity as an atomic property.

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1897
J. J. Thomson
Discovers the electron.

1900s

1900
Max Planck
Quantum science is born.

1905
Albert Einstein
Develops Special Theory of Relativity; later (in 1916) publishes General Theory of Relativity.

8

1912
Alfred Wegener
Proposes the continental drift theory.

1920s
Quantum mechanics emerges

1927
Georges Lemaître
Introduces big bang theory.

12

1929
Edwin Hubble
Successfully argues that the universe is expanding.

1930
Linus Pauling
Updates chemistry with ideas of quantum mechanics.

6

1938
Hans Spemann
Proposes the concept of cloning.

1939–45
Birth of nuclear technology

AP/US SIGNAL CORPS

1947
William Shockley, Walter Brattain, and John Bardeen
Invent the transistor.

1953
James Watson and Francis Crick
Publish the structure of DNA.

"It has not escaped our notice that the specific pairings we have postulated immediately suggests a possible copying mechanism for the genetic material."

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1953
Maurice Ewing and Bruce Heezen
Develop theory of tectonic plates.

1957
Soviets launch Sputnik.

1961
Murray Gell-Mann
Postulates the existence of quarks.

1962
Rachel Carson
Publishes *Silent Spring*, linking pesticide use to ecological ills.

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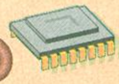
1969
The U.S. Department of Defense's Advanced Research Projects Agency creates ARPAnet, the precursor to the Internet and the World Wide Web.

1970
Hamilton Smith and Daniel Nathans
Develop first recombinant DNA techniques.

1970s
The Standard Model of particle physics emerges

1971
First commercial microprocessor manufactured.



1981
Acquired immunodeficiency syndrome (AIDS) recognized.

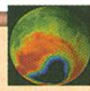
1990
Human Genome Project begins.

1992
World Wide Web demonstrated at CERN.

WWW.net

Mid-1980s
Kary Mullis
Develops polymerase chain reaction (PCR).

1985
Ozone hole discovered over Antarctica.



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1995
Bose-Einstein condensate created in laboratory.

M. R. MATTHEWS

1997
Ian Wilmut and Keith Campbell
Clone a sheep from adult cells.

1926: Alfred Wegener's theory of continental drift submerges due to the lack of support from his peers (to say the least). Forty years later, moving continents were established as scientific fact. The critical attitude always has been central to the scientific process, but it also can lead to the premature rejection of good ideas. This episode also is testimony to the faith among scientists that the truth will out.

World War II: Often known as "the physicists' war," WWII demonstrated tight links between science, technology, and national security. Synthetic rubber, radar, proximity fuses, and the fission bomb all emerged from the most extensive government-supported R&D program in history. After the war, this new R&D infrastructure evolved into its present form.

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1953: Without Rosalind Franklin's crystallographic data of DNA, James Watson and Francis Crick wouldn't have determined that molecule's structure when they did. The two of them and Franklin's senior co-worker, Maurice Wilkins, shared a Nobel Prize for the discovery. Franklin never received official credit for her contribution, and her role was written out of early historical accounts. Franklin represents the struggle for professional parity that women have waged, and continue to wage, in the scientific community.

The 20th century—The Janus Face of Science

Science has never been a value-free enterprise, and its double-edgedness expressed itself with a sobering regularity this century. Before there was "better living through chemistry," there were clouds of death-dealing chlorine on the Western Front of World War I. The next World War and the Cold War ushered in the awesome power of nuclear fission and fusion and a new kind of apocalyptic angst. Then came Rachel Carson. She alerted the world to global-scale ecological threats that can come with wide-scale environmental releases of synthetic chemicals. Her point was reiterated in the 1970s and 1980s when industrial activity and products were linked to planet-altering threats like ozone holes and global warming. Now, the growing ability to understand and manipulate our own genetic foundations opens up almost utopian medical possibilities. But that gleamy-eyed future only comes with the threat of unnerving compromises ranging from genetics-based job discrimination to the possibility of literally bumbling with the genetic constitutions of all generations that follow this one. Science has entangled itself within the most important values there are, and that brings with it unprecedented responsibilities for scientists of the next millennium.

Acknowledgments: Guidance for this graphic came from many books and other documents, as well as from the following historians: Robert Friedel, Naomi Oreskes, Steven Dick, Garland Allen, Spencer Weart, Sara Schechner, and James Fleming. The editors reserve credit for any remaining errors of fact or interpretation.