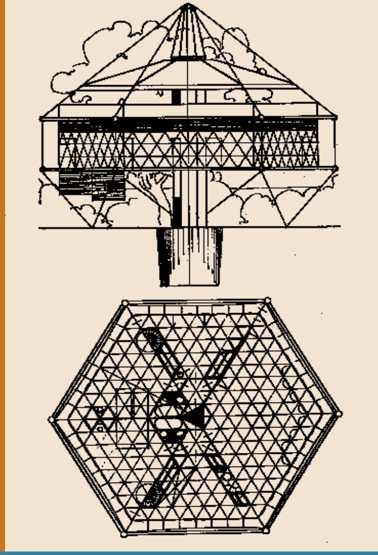
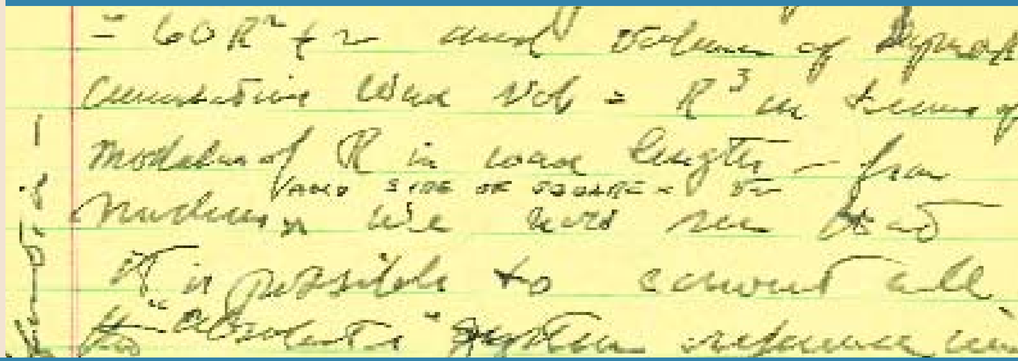




ALAN LIGHTMAN | MIT

Discovery

The urge to invent, to know the unknown, seems so deeply human that we cannot imagine our history without it. That passionate urge conquers the fear of the foreign, the fear of the gods, even the fear of personal danger and death. What remains is the pure exhilaration of discovery. Alan Lightman, novelist, essayist, physicist, and educator, explored some of the greatest scientific discoveries of the 20th century to find out whether any common patterns of discovery exist. With the help of fellow scientists who submitted nominations for the greatest discoveries in their fields, Lightman chose two dozen breakthroughs from physics, chemistry, and biology to use as case studies. Working with the original papers in which the discoveries were first announced, he found a great variety of scientific minds and discoveries, and identified a number of categories to describe them. Based on what he learned about how scientists arrive at their discoveries, Lightman offers several suggestions for how to best stimulate creativity and a spirit of discovery in students.

NOTEBOOK

Although there is clearly a wide range of processes in scientific discovery, some common patterns emerge. Most discoveries involve a synthesis, bringing together different strands of information and ideas and connecting them.

A prepared mind is the critical first step of discovery. There are no examples of major scientific discoveries in the 20th century made by untrained amateurs.

In addition to mastering the facts, learning how to think like a physicist or biologist, for example, is essential. This way of thinking can be cultivated by giving students the opportunity to brush shoulders with the leading practitioners in their fields.

There is no single scientific personality type—despite the general public's stereotypical notion of scientists.

A Taxonomy of Scientific Discovery

No one knows exactly what happens in the creative process or what chain of mental and external events leads to recognition and discovery. Indeed, there is a broad range of processes in scientific discovery, and any scheme to classify them is subjective; further, many discoveries are messy affairs and spill over into several categories. That said, I propose a tentative taxonomy, with the hope of stimulating further discussion. It includes eight classes of discovery—a relatively large number from a sample of only two dozen case studies. The real test of this taxonomy will be to see what proportion of other discoveries fit or do not fit into it.

The Accident, in which the scientists discover something they were not looking for. This category breaks down into (a) discoveries whose significance the scientists did not understand at the time and (b) discoveries whose significance was immediately appreciated.

A good example of (a) is the discovery of cosmic background radiation by Arno Penzias and Robert Wilson in 1965. Those scientists, both excellent experimentalists, had no other explanation for the residual hiss in their radio antenna, corresponding to a background cosmic temperature of about 3 kelvin. An example of (b) is Alexander Fleming's discovery of penicillin in 1928. Although Fleming was completely surprised to discover a white mold growing on his culture of staphylococci that dissolved the staphylococci nearest it, he instantly recognized that he had stumbled upon an antibacterial agent.

Principles First, in which the scientist begins with a philosophical principle and explores its consequences, sometimes initially unaware of the precise problem to be solved. The application of the foundational principle can, in fact, define both the problem and its solution. The premier example of this rarified category was Einstein's work on special relativity, in which the physicist began with the "symmetry" principle that all frames of reference moving at a constant velocity relative to each other are equivalent. In the process of working out the consequences of this starting principle, Einstein discovered that our notion of time had to be reconceived.

Principles Last, in which the scientist engages in concentrated work to explain a particular experimental result and ultimately recognizes that a new fundamental theoretical idea is required. Max Planck's discovery of the quantum in 1900 illustrates this category. The German physicist was trying to use the methods of thermodynamics and statistical physics to justify his own ad hoc formula for black-body radiation (itself a discovery). To do so, he had to assume that the energies of his "vibrating resonators" were not continuous and infinitely divisible but came in whole lumps—the quanta.

The Timely Clue, in which the scientist is confronted with an important clue while struggling with a recognized problem. An example of this category is Barbara McClintock's discovery in 1948 that genes can move around on chromosomes. While pondering how pigment-controlling genes in corn plants were turning on and off during the growth of a single plant, McClintock noticed one day that mutations on corn leaves came in pairs. McClintock later recalled that "the twin sector phenomenon was so striking that I dropped everything…I felt sure that I would be able to find out what it was that one cell gained and the other cell lost."

These patterns of discovery are probably universal to the creative process in general and occur in the arts as well as in the sciences. Writers, for example, have given similar accounts of their creative processes in dozen of interviews in *The Paris Review* over the last two or three decades.

Scientists need a good understanding and vision to recognize the importance of the clue. A clue that comes before its time is of no use. For example, the remarkable fit of the opposite coasts of South America and Africa, like adjacent pieces of a jigsaw puzzle, was known for centuries but never recognized as a clue to the ancient geography of the Earth until Alfred Wegener proposed his theory of continental drift in 1912, along with the radical idea that land masses could move horizontally across the face of the Earth.

Analogy, in which the scientist applies a concept or pattern from a previous problem. An example of this kind of process was Hans Krebs's 1937 discovery of the citric acid cycle, also known as the Krebs cycle. Krebs and other biochemists were trying to discover what chain of chemical reactions was responsible for respiration—that is, the combination of oxygen with carbohydrates and fats to release energy in living organisms. Other scientists had found pieces of the chain. Several years earlier, Krebs had made the first discovery of a cyclic process in biochemistry, the ornithine cycle, in which ornithine is changed to citrulline, which is changed to arginine, and then back to ornithine, ready to begin the cycle again. Along the cyclical path, the toxic molecule ammonia is converted into urea and removed from the body. The citric acid cycle converts citric acid into a sequence of other substances, eventually returning to citric acid, while hydrogen atoms are pulled off the intermediate molecules to combine with oxygen to form water and release energy.

Krebs had cycles on his mind. The scientist searched for the missing chemical reactions and substances that would regenerate citric acid, thus allowing the sequence of steps to occur in a continuous loop. As he wrote in his memoir, "In visualizing the cycle mechanism it was of major relevance that five years earlier I had been concerned with the first metabolic cycle to be discovered, the ornithine cycle of urea synthesis."

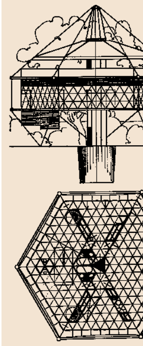
The Mathematical Imperative, in which a theoretical scientist, in exploring the mathematical world, is led to a discovery about the physical world. A prominent example of this type of discovery was Paul Dirac's discovery in 1928 of the equation describing the electron. The requirement that such an equation embrace both relativity and quantum mechanics in turn necessitated a particular mathematical structure. In following the narrow path of this mathematical landscape and its internal logical consistency, Dirac was directed to his discovery.

New Tools, in which the availability of new instruments or new theories opens up opportunities for discovery. On the experimental side, this category might be further divided into (a) an inspired idea of how to use a new technology and (b) privileged access to new technology.

An example of (a) is Max von Laue's realization in 1912 that the regular spacing of atoms in a solid crystal would serve as a three-dimensional diffraction grating whose structure could be probed with a collimated beam of X-rays, just as a one-dimensional diffraction grating spreads a monochromatic beam of visible light. X-rays were new at the time. Furthermore, they were known to have wavelengths comparable to the spacing between atoms in solids, which was just what was needed for the job.

An example of (b) was Edwin Hubble's discovery in 1929 that the distances to galaxies are approximately proportional to their recessional velocities, a fact later used to support the notion that the universe is expanding. Other scientists were also attempting to measure the distances to a group of exceptionally fast-receding galaxies discovered by Veston Melvin Slipher. Hubble's advantage lay in his exclusive access to the relatively new 100-inch Hooker telescope on Mount Wilson in California, at that time the largest telescope in the world.

The Long Haul, in which steady, incremental work on a recognized problem over a long period of time leads to discovery. An example is Max Perutz's discovery of the three-dimensional structure of hemoglobin, one of the first protein structures to be worked out. Perutz and his team worked on the problem for 22 years, from 1938 to 1960, painstakingly producing and analyzing hundreds of X-ray diffraction photographs and refining their experimental technique along the way.



Patterns of Discovery

Although there is clearly a wide range of processes in scientific discovery, some common patterns emerge. Most discoveries involve a synthesis, bringing together different strands of information or ideas and connecting them. Another pattern that occurs in many, but not all, scientific discoveries is this sequence of events: (1) research and hard work, leading to a "prepared mind," followed by (2) being stuck on a problem, and (3) experiencing a shift in thinking or perception that leads to the breakthrough.

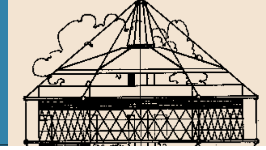
A prepared mind is the critical first step. I know of no examples of major scientific discoveries in the 20th century made by untrained amateurs. Even when the discovery is accidental, it requires a prepared mind, as in Fleming's discovery of penicillin in 1928. Fleming had been working on antibacterial agents for 20 years, beginning with his medical school thesis in 1908. Another step, being stuck on the problem, played a role in roughly half of the major discoveries I investigated.

Interestingly, these patterns of discovery are probably universal to the creative process in general and occur in the arts as well as in the sciences. Writers, for example, have given similar accounts of their creative processes in dozens of interviews in *The Paris Review* over the last two or three decades.

There is no single scientific personality type—despite the general public's stereotypical notion of scientists. Great scientists can be bold and self-confident revolutionaries, like Einstein, or they can be modest and diffident, like Krebs and Fleming. What all of these scientists—men and women alike—share is a passion to know, a sheer pleasure in solving puzzles, and an independence of mind.

Stimulating Creativity and Discovery

How can this taxonomy of discovery inform teaching and learning on our campuses today? First, it is clear that a strong grounding in the tools and fundamentals of the discipline is critical—that is, students' minds must be



prepared to enable them to make important contributions to their field. In addition to mastering the facts, learning how to think like a physicist or biologist, for example, is essential. Max von Laue, whose interest was in optics and the wavelike behavior of light, recalled about his path-breaking work, “I had finally been able to cultivate what one could almost term a special feeling or intuition for wave processes.” Many of the world’s greatest scientists, from Einstein to Richard Feynman, have attempted to describe this “special feeling.” In part, it is the ability to comprehend a thing from several points of view, and to visualize a phenomenon, even one that is not visible to the eye. This way of thinking about a subject can be cultivated by giving students the opportunity to brush shoulders with the leading practitioners in their fields, perhaps through research projects, lectures, or small classroom discussions.

Further, students—including undergraduates—should be given opportunities for independent research projects to encourage their own thinking and learning, and be given open-ended assignments that have no clear path to a final answer to stimulate their creativity. Finally, students who get stuck on problems should be supported and encouraged to continue to work on them so that they don’t give up. As history shows, being stuck on a problem is an important and normal part of the creative process.

Students—including undergraduates—should be given opportunities for independent research projects to encourage their own thinking and learning, and be given open-ended assignments that have no clear path to a final answer to stimulate their creativity.

Conclusion

Measuring in powers of 10, we human beings are almost exactly midway between the largest material objects in the universe, the galaxies, and the smallest that we have explored in our particle accelerators, the electrons and quarks. We stand in the middle. From our thin sliver of existence we want to know everything—the intricacies and the sweeping principles, the secrets of life, and the nature of time and space. We are driven to know. We discover, we invent, we create, we question. We can further these endeavors by encouraging our students to embark upon journeys of discovery that ultimately will deepen human knowledge and add to the beauty and mystery of our existence.

Note: Much of this summary was originally published in Alan Lightman, “Scientific Moments of Truth,” New Scientist, *19 November 2005.*

ALAN LIGHTMAN is a novelist, essayist, physicist and educator. His book, *Einstein’s Dreams* (1994), was an international bestseller and has been translated into 30 languages. His most recent book is *The Discoveries: Great Breakthroughs in 20th Century Science* (2005).