Is Science Mostly Driven by Ideas or by Tools?

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HISTORY OF SCIENCE

Is Science Mostly Driven by Ideas or by Tools?

The physical sciences have alternated between revolutions driven by new ideas and explorations driven by new tools.

Freeman J. Dyson

Thomas Kuhn was a theoretical physicist before he became a historian. He saw the history of science through the eyes of a theorist. He gave us an accurate view of events in the world of ideas. His favorite word, "paradigm," means a system of ideas that dominate the science of a particular place and time. A scientific revolution is a discontinuous shift from one paradigm to another. The shift happens suddenly because new ideas explode with a barrage of new insights and new questions that push old ideas into oblivion. I remember the joy of reading Kuhn's book, *The Structure of Scientific Revolutions*, when it first appeared in 1962. It made sense of the relativity and quantum revolutions that had happened just before the theoretical physicists of my generation were born. Those were revolutions led by deep thinkers—Einstein and Heisenberg and Schrödinger and Dirac—who guessed nature's secrets by dreaming dreams of mathematical beauty. Their new paradigms were created out of abstract ideas. In those revolutionary years from 1900 to 1930, ideas led the way to understanding.

Peter Galison published in 1997 a fatter but equally illuminating book, *Image and Logic*. Galison gives us a different view of history. He was an experimental physicist before he became a historian. His history is dominated by tools as Kuhn's was dominated by ideas. Galison does not contradict Kuhn. He quotes Kuhn from time to time with approval. But there is hardly any overlap between the two accounts. The main theme of Galison's book is the transition from the analog world of cloud chambers and bubble chambers to the digital world of counters and computers in the history of 20th-century particle physics. Analog devices producing pictures were superseded by digital devices producing numerical data. This transition was a profound change. It occurred not only in particle physics but also in other sciences such as geology, meteorology, paleontology, and genetics. Perhaps astronomy is the last remaining science that still has its main tools producing output in the form of images. Even in astronomy, though,

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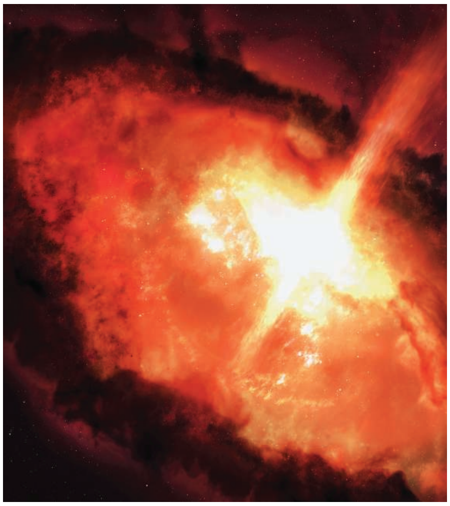

digital output is rapidly gaining ground. The tools of digital data-processing have driven progress in almost all the sciences during the second half of the 20th century. Broadly speaking, the first half of the 20th century belonged to Kuhn and the second half to Galison. Kuhn and Galison are both excellent historians, but each of them depicts a partial view of science. We need both of them to give us a complete picture.

Kuhn's book covers 500 years from Copernicus to the present. Galison covers less than a hundred. Kuhn gives us vivid accounts of idea-driven revolutions before the 20th century, especially the revolutions associated with the names of Galileo in physics and Lavoisier in chemistry. In those earlier centuries, Galisonian science was already important. The tools of steam-engine technology came first, before the ideas of thermodynamics. The tools of telegraphy and telephony came first, before the ideas of information theory. Kuhn was well aware that Galisonian science existed, but he dismissed it with the epithet "normal." Kuhn concentrated his attention on scientific revolutions. Normal science was by definition not revolutionary and therefore not interesting.

At the midpoint of the 20th century, when I was a student, the two books had not yet been written, but the world of physics was sharply split into Kuhnian and Galisonian programs. The old heroes of the pre-war revolutions were pursuing private dreams of Kuhnian revolutions still to come. Einstein dreamed of a unified field theory. Heisenberg and Schrödinger and Dirac each had a dream based on equations rather than on experiments. Each of them believed that progress in physics could only come through revolutionary new ideas. Each of them dreamed of repeating the triumphs of the 1920s. Meanwhile, the younger generation was using the new tools generated by military technology to push science ahead in Galisonian style. Martin Ryle at Cambridge University was salvaging abandoned military radar dishes and converting them into radio telescopes to explore the universe. He found an astonishing abundance of powerful radio sources at cosmological distances. Willis Lamb at Columbia University was using microwave spectroscopy to explore the fine structure of the hydrogen atom with vastly improved precision. He found evidence for interaction of the atom with charges and currents induced by it in empty space. Maurice Wilkins and Rosalind Franklin at Kings College, London, were using x-ray diffraction to explore the structure of DNA. Their pictures led Francis Crick and James Watson to the discovery of the DNA double helix. Melvin Calvin in Berkeley was using radioactive tracer chemistry and paper chromatography to explore photosynthesis. He found the chain of reactions by which plants use sunlight to convert carbon dioxide into sugar. Four new tools created four new sciences. Ten years after World War II ended, Galisonian science was roaring ahead while Kuhnian dreams had faded. And so it continued for the rest of the 20th century.

At the beginning of the 21st century, we find ourselves in a situation reminiscent of the 1950s. Once again, the community of physicists is split into Kuhnians and Galisonians. The most ambitious of the Kuhnian programs is string theory, building a grand and beautiful structure out of abstract mathematics and hoping to find it somehow mirrored in the architecture of the universe. This program is not an isolated one-man show like Einstein's unified field theory. String theory is a collective enterprise combining the efforts of thousands of people in hundreds of universities. These people are the best and the brightest of their generation, most of them young and

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many of them brilliant. Their work is admired by the pure mathematicians who share their ideas and speak their language. String theory, as a solid part of modern mathematics, is here to stay. But meanwhile, Galisonian science is continuing to forge ahead, exploring nature without paying attention to string theory. The great recent discoveries in the physical sciences were dark matter and dark energy, two mysterious monsters together constituting 97% of the mass of the universe. These discoveries did not give rise to new paradigms. We cannot build paradigms out of ignorance. The monsters were discovered by using the new tools of astronomy, wide-field cameras, and digital data processing. We must study the monsters patiently with new and more precise digital tools before we can begin to understand them. Galisonian science will continue to explore, with constantly evolving tools, the structures of space and time and galaxies and particles and genomes and brains.

We are standing now as we stood in the 1950s, between a Kuhnian dream of sudden illumination and a Galisonian reality of laborious exploring. On one side are string theory and speculations about multiverses; on the other are all-sky surveys and observations of real black holes. The balance today is more even than it was in the 1950s. String theory is a far more promising venture than Einstein's unified field theory. Kuhn and Galison are running neck and neck in the race for glory. We are lucky to live in a time when both are going strong.

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HISTORY OF SCIENCE

The Revolution in the Life Sciences

Recognition of DNA as the carrier of information created a new fundamental dimension for viewing the natural world.

Sydney Brenner

Historians have the luxury of looking back at human endeavor over long periods of time, but most scientists are too busy working in the present and thinking anxiously about the future and have no time to view their work in the context of what has gone before. I once remarked that all graduate students in biology divide history into two epochs: the past 2 years and everything else before that, where Archimedes, Newton, Darwin, Mendel—even Watson and Crick—inhabit a time-compressed universe as uneasy contemporaries. It seems remarkable that historians once thought that science progressed by the steady addition of knowledge, building the edifice of scientific truth, brick by brick. In his 1962 book *The Structure of Scientific Revolutions*, Thomas Kuhn argued that progress occurs in revolutionary steps by the introduction of new paradigms, which may be new theories—new ways of looking at the world—or new technical methods that enhance observation and analysis.

Between Kuhn's revolutions, scientific knowledge does advance by accretion, as there is much to do to consolidate the new science. But then, inevitably, unsolved problems accumulate and, in many cases, the inconsistencies have been put to one side and everybody hopes that they will quietly go away. The edifice becomes rickety; some of its foundations are insecure and many of the bricks have not been well-baked. This is when a new revolutionary wave in the form of new ideas or new techniques appears, which allows us to condemn and demolish the unsafe or corrupt

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parts of the edifice and rebuild truth. Often there is great resistance to the new wave, but as Max Planck pointed out, it succeeds because the opponents grow old and die. The process is then repeated: The radicals become liberals, the liberals become conservatives, the conservatives become reactionaries, and the reactionaries disappear. Students of evolution will recognize this process in the theory of punctuated equilibrium: Organisms stay much the same for very long periods of time; this is interrupted by bursts of change when novelty appears, followed again by stasis.

The life sciences have undergone a radical revolution in my lifetime, and it is interesting to view this from the vantage point of the present to understand its full meaning and impact. In the first half of the 20th century, physics underwent two revolutions: Einstein's theory of relativity, connected with large scales of time and space, and quantum mechanics, concerned with the very small and dealing with fundamental questions of matter and energy. Although Newton still reigned supreme in the human-scale world, the revolutions opened up totally new fields of the physical sciences whose impact continues today. In the meantime, genetics had shown that chromosomes were the carriers of genes that specified the phenotypic characteristics of organisms and were the modern version of the factors postulated by Mendel—but beyond that, very little was known about the material basis of genes and how they accomplished their proposed functions in living organisms. This property attracted the attention of theoretical physicists; one, Schrödinger, wrote a book (*What Is Life?*) that speculated on the physical nature of the genetic material. Many of my contemporaries read this book and claimed it had a great influence on them. I read it but did not understand it, largely because I did not know what Schrödinger meant by an aperiodic crystal. Later, I came to realize that he had made a profound error when he claimed that the chromosomes not only contained the plan for the development of the organism but also had the means to execute it.

Chromosomes were known to contain both DNA and proteins, but many biologists did not believe that DNA could be the carrier of genetic information because its chemical structure was too simple; they thought proteins had to be involved. Avery's demonstration that DNA was the transforming principle of *Pneumococcus* was ignored by most biochemists, but in 1953, the discovery of the double-helical structure of DNA by Watson and Crick changed everything. Very little happened in the first few years, but by 1956, the new molecular biology began to gather momentum, and the rest of the story is well known.

We can now see exactly what constituted the new paradigm in the life sci-

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