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Creativity and Science. Part 2. The Process of Scientific Discovery

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Concluding a two-part examination of creativity research, this essay discusses some of the factors involved in the process of scientific creativity and discovery. Such mental tools as intuition and imagination are considered, as is the role of anomaly. Citation-based analysis and mapping of the scientific literature, and their relevance to various forms of discovery, are also discussed.

When I spoke on the topic of creativity last October for the 12th annual Perey Research Lectureship at McMaster University, Hamilton, Ontario, Canada, I never imagined it would prove such a rewarding experience.

While there, I discovered that this university has offered for close to 20 years what is considered to be one of the most progressive and innovative medical-school programs in the world. In fact, in a review of factors influencing medical students' choice of a specialty, R.M. Mowbray, professor of clinical psychology, Memorial University of Newfoundland, St. John's, Canada, observed, "McMaster has an international reputation as an innovative school in its emphasis on problem-solving, self-learning, small-group teaching in the curriculum, and its selection of students based on their personal characteristics rather than their academic grades."[1]

The experience at the McMaster school was especially exhilarating for me since it showed how modern information resources can be used creatively in the educational process. Imagine a medical school where the typical student has been out of college for several years, where a tutor is assigned to a group of five students, where lectures are rare and attendance purely voluntary, and where the utilization of audiovisual educational programs is unparalleled. We hope to devote a future essay to this problem-solving approach to medical education.

However, the subject of this essay is creativity. In Part 1 we covered some of the many definitions of creativity and examined the literature of creativity research.[2] This second part concerns the role creativity plays in the process of scientific discovery.

Discovering

The process of scientific discovery was recently brought to widespread public attention by the furor over so-called "cold fusion" or "fusion in a jar." As *Business Week* put it, last spring B. Stanley Pons, University of Utah, Salt Lake City, and Martin Fleischmann, University of Southampton, UK, appeared to have unlocked "the nearly limitless energy of nuclear fusion...with little more than a car battery, a palladium electrode, and a bottle of water in a Rubbermaid dish pan."[3]

What followed the astonishing claim of sustainable, room-temperature nuclear fusion was a race among physicists and chemists throughout the world to verify the results, even as most scientists expressed extreme skepticism that the claims could possibly be true.[4] Early reports of confirmation of Pons and Fleischmann's results came from Brigham Young University, Provo, Utah, and other labs.[5] As time went by, however, more and more attempts at verification produced negative results; something unusual did seem to be happening within the simple electrochemical cells, but it could not conclusively be shown to be fusion.[6] However, as John Maddox noted in an editorial in *Nature*, "Fleischmann and Pons have done at least one great service for the common cause: they have kindled public curiosity in science to a degree unknown since the Apollo landings on the Moon.... It is remarkable that so many people are willing to accept that experimental observations, and the inferences drawn from them, acquire validity only by replication. Has what used to be called 'the scientific method' now become widely understood?"[7]

In my talk at McMaster, I spoke of another recent and prior example of the scientific discovery process that came to public attention (though not in so dramatic a fashion): the work in superconductivity by Karl Alex Müller and Johannes Georg Bednorz, IBM Zurich Research Laboratory, Rüschlikon, Switzerland.[8] Their breakthrough article was published in 1986 and, with most unusual speed, they were awarded the Nobel Prize in physics the very next year.[9] They achieved superconductivity at 30 kelvin (K)—an unprecedented discovery; previously, materials had become superconductors only at temperatures approaching absolute zero (0 K). Absolute zero on the Kelvin scale is equivalent to minus 273.15 degrees Celsius.

In a sequence of events that paralleled the later announcement of cold fusion, laboratories throughout the world raced to discover substances that become superconductors at even higher temperatures. The first to come up with such a substance were Paul Chu and colleagues, University of Houston, Texas, and Maw-Kuen Wu and colleagues, University of Alabama, Huntsville, who discovered a compound of yttrium, barium, copper, and oxygen that becomes superconducting at liquid-nitrogen temperatures (93 K).[10]

The events leading to this discovery are explored in great detail in a book entitled ***Breakthrough: The Race for the Superconductor*** by Robert M. Hazen.[10] Hazen's account emphasizes the importance of good preparation and a rational, systematic approach to a problem. But he also demonstrates the importance of "intangibles" such as imagination and intuition, as shown by the advice of a senior colleague to Chu:

> Of the many lessons that [Bernd] Matthias [noted elder statesman of superconductivity at Bell Labs] taught Paul Chu about the scientific process, the most important ones were not to be found in any textbook. "Follow your hunches; use your intuition," he would say. He taught Chu to scan the scientific literature regularly and systematically for promising new materials, techniques, or theories that might help in understanding the mystery of superconductivity. He told Chu to listen to his dreams.[10] (p. 21)

Creativity in the Process of Scientific Discovery

Matthias's advice is timeless. One assumes that such use of intuition occurs not only among creative scientists, but among all creative people in every field of activity. Nevertheless, these are only a few of the many facets of the process of discovery and the still little-understood workings of the creative mind.

Intuition was also listed among the essential creative qualities for scientists by one of the first recipients of the MacArthur Prize, biochemist/historian Robert Scott Root-Bernstein, Michigan State University, East Lansing. Root-Bernstein has used his award money to pursue a long-cherished dream of writing a book about the process of making scientific discoveries. Drawing upon the notebooks, diaries, and correspondence of a number of leading biologists and chemists of the nineteenth and twentieth centuries, Root-Bernstein has been exploring the conditions that fostered the process of discovery and the attributes that enabled these scientists to see what others had overlooked.[11]

For Root-Bernstein this process is not simply a matter of being in the right place at the right time. Instead, he says, "how a scientist *interprets* what he sees depends on what he expects." Thus, discoveries owe much to the ways in which the scientists who make them go about their work. Since each scientist has a different work style, and since not all scientists make discoveries, Root-Bernstein concludes that "it should be possible to identify the styles that most often pay off.... Any mental activity that contributes directly to scientific discoveries should be recognized as scientific method."[12]

Mental Tools of Discovery

Root-Bernstein identifies several mental qualities that seem essential to the process of scientific discovery, including (but certainly not limited to): game playing ("a willingness to goof around"); a facility for cultivating a "degree of chaos"; a tendency toward "universal thinking" (the ability to elevate the seemingly trivial to the universal, or the application of fundamental principles to diverse phenomena); a personal identification with the subject of investigation; intuition; and a facility for recognizing patterns.[12]

But these merely provide the fertile ground in which a discovery may take root and blossom. Examining scientific discovery in his book *The Structure of Scientific Revolutions*, Thomas S. Kuhn, Massachusetts Institute of Technology, Cambridge, discussed the importance of anomaly. "Discovery," he wrote, "commences with the awareness of anomaly, i.e., with the recognition that nature has somehow violated the paradigm-induced expectations that govern normal science. It then continues with a more or less extended exploration of the area of anomaly. And it closes only when the paradigm theory has been adjusted to so that the anomalous has become the expected."[13]

Root-Bernstein also touches on this theme. The heart of the discovery process, as he observes, is the rise of an anomaly, an unexpected result or new problem, that alters thinking and leads to the discovery itself:

> Discovery...is the inevitable, if unforeseen, consequence of a rational and carefully planned line of inquiry initiated by a scientist.... Contrary to...orthodoxy, the tests of an incorrect hypothesis often result in surprises that lead to discovery.... [Discoverers] seem to have ways of courting the unexpected, which improve their chances of making novel observations.... Important discoveries arise not from verification or disproof of preconceptions, but from the unexpected results of testing them.[12]

The Human Side of Science

A significant problem for the philosopher or historian of science, or for anyone interested in the various facets of scientific creativity, is that the forms and conventions of scientific publications tend to give a false impression about the way research is really done. In a 1963 BBC radio lecture later published in *The Listener*, Sir Peter B. Medawar, National Institute for Medical Research, London, cowinner of the 1960 Nobel Prize in physiology or medicine, went so far as to label the scientific paper a "fraud." As he clarifies, "I mean the scientific paper may be a fraud because it misrepresents the processes of thought that accompanied or gave rise to the work that is described in the paper." According to Medawar, the traditional, inductive format of the scientific paper should be discarded, with the "discussion" section moved from its customary place at the end of the paper to the beginning. "The scientific facts and scientific acts should follow the discussion," says Medawar, "and scientists should not be ashamed to admit, as many of them apparently *are* ashamed to admit, that hypotheses appear in their minds along uncharted by-ways of thought; that they are imaginative and inspirational in character; that they are indeed adventures of the mind."[14]

Sociologist Robert K. Merton, Columbia University, New York, examines the same problem in his 1968 book *Social Theory and Social Structure*. "Typically," he notes, "the scientific paper or monograph presents an immaculate appearance which reproduces little or nothing of the intuitive leaps, false starts, mistakes, loose ends, and happy accidents that actually cluttered up the inquiry.

The public record of science therefore fails to provide many of the source materials needed to reconstruct the actual course of scientific developments."[15] As noted by Julius H. Comroe, now deceased but then director, Cardiovascular Research Institute, University of California, San Francisco, "For those seriously interested in learning more about the process of scientific discovery, the scientist...rarely tells it like it was."[16]

It is relevant to note that my own interest in precisely these aspects of the scientific discovery process was one of the prime reasons for introducing the *Current Contents*® (*CC*®) feature called "This Week's Citation Classic®" more than 10 years ago.[17] *Citation Classics* are highly cited books or papers that generally have had great impact in their respective fields. In the commentaries we solicit from authors, we ask that they describe the genesis of their research and the circumstances that affected its publication and eventual acceptance by the scientific community. We encourage them to include personal details that are rarely found in formal scientific articles and to speculate on reasons for their work becoming so highly cited. Aside from supplying grist for the mill of historians and sociologists of science, these commentaries provide insight into science as an eminently and fundamentally human endeavor. Over 2,000 of them were collected in a seven-volume series called Contemporary Classics of Science.[18-23]

An example of the light shed by these commentaries on the discovery process comes from Robert H. Wasserman, Department of Physiology, Cornell University, Ithaca, New York, and Alan N. Taylor, Department of Anatomy, Baylor College of Dentistry, Dallas, Texas. As they note in their commentary, they provided the first conclusive evidence of the existence of a specific calcium-binding protein synthesized in response to vitamin-D administration—which wasn't what they'd been looking for at all. In attempting to "quantitate the compartmentalization of calcium...during the absorption process," Wasserman and Taylor discovered that prior administration of vitamin D had a "pronounced effect" on calcium distribution, and ultimately proved the existence of "the unique...vitamin-D-induced calcium-binding protein."[24]

Many scientists can also readily identify with the experience of John T. Rotruck, Department of Biochemistry, University of Wisconsin, Madison. As a graduate student, and with the enthusiastic help and advice of his senior colleague W.G. Hoekstra at the University of Wisconsin, Rotruck was the first to demonstrate a specific role for selenium in mammals.[25] In the discussion of this work, he notes that, "in fact, some [experts and professors] discouraged us from pursuing this line of research because they didn't think it was possible that selenium could be part of an enzyme." Nevertheless, with Hoekstra's encouragement, Rotruck eventually discovered selenium's role as an integral part of glutathione peroxidase.[26]

These commentaries—and many more—illustrate the kind of behind-the-scenes information that helps sensitize students and others to the diverse nature and methods of science. They also constitute another avenue by which scientists can become recognized for their contributions. As we know, not all discovery or creativity is explicitly rewarded with prizes. Formal awards are only the tip of an enormous iceberg of the recognition that scholars not only seek—consciously or otherwise—but also receive. Discussing the reward system of science, Merton referred to citations as part of the coinage of the scientific realm.[27] On several occasions I have applied a similar metaphor, discussing citations as the currency of science.[28]

The Sociology of Scientific Discovery

Science is a large, global enterprise. And yet, it has the characteristics of a relatively small community. Scholars play some fascinating games to test the "small-world" theorem. We discussed the small-world phenomenon in an essay a decade ago.[29] The output of almost any research institution is linked in the formal literature, and by in-formal contacts, to the outputs of almost all other research institutions in the world.

To express this notion another way, if you imagine the literature as consisting of a multidimensional network of publication events linked by citations, you can trace a path from any paper in the network to any other paper without a gap. In graph theory, this might be expressed more concisely. But in lay terms, it simply implies that all discoveries can be associatively linked, if you allow your imagination to transverse the network. We have incorporated this notion into a powerful new tool for information discovery that is part of the *Science Citation Index®* (*SCI®*) on CD-ROM.[30]

For over 25 years now, you have been able to use the print *SCI* to find out who has cited a particular paper or book. And, by extension, you could find who has cited simultaneously two different papers or authors you might specify. Now, however, having located a particular reference using the *SCI Compact Disc Edition*, you can employ bibliographic coupling to explore other papers that share cited references with your selected item. We call this feature "related records," and it allows you to expand your search instantly, without relying on title words or other traditional indexing methods.

In addition to citation analysis, other tools from the sociology of science can also add quantitative weight to the qualitative insights I have mentioned. These tools include bibliometrics, scientometrics, and other research into science indicators. The late Derek J. de Solla Price, as well as mathematician and information scientist Manfred Kochen, often expressed their dreams of "mapping" fields of scientific and technical knowledge in the same way that cinematic versions of the "war room" in the Pentagon depict the current status of various military forces.[31,32] In fact, Price, in his flamboyant fashion, once went so far as to hope that such a map of science could come complete with flashing lights that would indicate that a breakthrough was about to occur in, say, China, in the field of molecular biology.[31] I am sorry to say we don't yet have such a capability. However, the rapid increase in computer power and storage capacity has made it a realistic goal likely to be achieved fairly soon.

Creatively Fostering Future Creativity

We cannot ignore what these methodologies tell us about the way science cumulates. You cannot separate the two facets of information retrieval—information recovery, as in the French *retrouver*—and information discovery. A colleague once described all this as "systematic serendipity": you know where you would like to begin, but you don't know where it will lead.

Citation tracing or coupling tells you about the unexpected connections that exist between your work and that of others—past, present, and future. And, indeed, we have reason to believe that, at various levels of clustering, citation associations will facilitate discovery by revealing connections that may otherwise have been missed.

So when I rhapsodize about the mapping of science literatures, it is not just because the maps themselves provide pretty pictures; they enable the informed creative mind to visualize connections that cannot be made from reading indexes. Can you imagine using a road map expressed simply as an alphabetic list of cities just giving their longitude and latitude? The brain is not equipped to handle the implicit associations that stand out at once in a graphic presentation of the same information. That is why Price and other early information explorers visualized the mapping of science in the metaphor of the command and control map at a military headquarters. Powers of visualization may be one of the unexplored areas of creativity research in science that needs pursuing. Is this the art in science that is so evident? Surely this is related to the enormous growth in computer-aided graphic displays.

Library and information science can contribute actively to the discovery process in other ways than these. Library and information workers have long assumed that they contribute to the creativity and problem-solving ability of scientists, but they had no formalized, concrete evidence of this. However, advances in data-retrieval systems and artificial intelligence can help information workers participate more actively, as more nearly a full partner, in discovery. Such advances, as discussed by David Bawden, Pfizer Central Research, Kent, UK, include the capability to detect analogies, patterns, and exceptions and the expansion of browsing capabilities, which enhance not only the interdisciplinary nature of the information obtained but also the serendipitous use of the literature—the value of which one sees time and again.[33]

But, of course, discovery and creativity are not dependent upon the literature alone. The pattern of discoveries revealed through a content analysis of scientific bibliographies tells us much about the human side of discovery. It is not an easy task to catalog the most frequent elements in the minibiographies we publish in *CC*.

One might, for example, conclude that the predoctoral period is the most fertile source of discovery, considering the large number of *Citation Classics* that were based on doctoral theses. A young, fresh viewpoint may make for discovery (and for error, too) but then we have plenty of evidence that youth is a frame of mind rather than a physical condition. A number of older scientists may get bogged down in administration, but those who choose not to, or choose to move into entirely fresh, new areas, can also bring youthful insight to an old problem. This may be the case with the wave of interdisciplinary discoveries in the past few decades. But, of course, arguments against overspecialization can be countered by the need to focus intensively on one problem.

Conclusion

We have reviewed a very small part of the fairly recent literature of research on scientific creativity. However, to borrow a quote from UCLA zoologist George A. Bartholomew, "I am not so completely lacking in perspective that I would undertake to tell any working scientist how to increase his or her creativity."[34]

As Bartholomew notes, however, most scientists are also teachers of future scientists, and these young scholars *can* use the help. And it does seem to me that young (and some not-so-young) scientists can profit from the words of psychologist Janet Beavin Bavelas, University of Victoria, British Columbia, Canada, who wrote that

> scientific research...can be differentiated into stages, and the activities appropriate to later stages are premature and infelicitous at the beginning. The critical and analytical way of thinking that is vital in the final stages leads to the certain death of creativity in the early stages.... Usually we immediately apply to a novel observation the same standards that should be applied to a fully mature hypothesis, and of course, a newborn observation cannot withstand such treatment.[35]

But if her advice (put simply) is, "Loosen up!", Bavelas also points out the catch:

> If the undergraduate years are devoted to getting the grades to get into graduate school, and the graduate years are devoted to getting the degree and publishing in order to get an academic position, and the first several years of this assistant professorship are devoted to getting tenure, *then* are you going to do original work you believe in? After more than 12 years of accommodation, the very least one could expect is a period of re-education, which the "system" does not provide for.[35]

What Bavelas and others are telling us is that only the strongest creative personality may be able to withstand the onslaught of the formal systems we have maintained. But, given the atmosphere of freedom and institutional support, there seems to be plenty of evidence that many suppressed personalities may thrive under the right conditions. I believe this was the message delivered by the 1987 Nobel Prize winner in medicine, Susumu Tonegawa, when he advised the Japanese how to restructure science in Japan to encourage even greater creativity in basic research.[36]

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