Creativity in Science

CHANCE, LOGIC, GENIUS, AND ZEITGEIST

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Contents

1

Introduction: Scientific Creativity

Consider the following list: Newton's *Principia Mathematica*, Plato's *Republic*, Shakespeare's *Hamlet*, da Vinci's *Last Supper*, and Beethoven's *Fifth Symphony*. What do these items have in common? The answer clearly is that all five represent creative products, even works of genius. Each can be considered an exemplary contribution to a particular domain of creative achievement. Each of these creations exerted a profound and pervasive influence on the collective repository of human accomplishments that defines world civilization.

Yet in one crucial respect, one of the items on this list does not belong with the rest: Newton's scientific masterpiece. Unlike the others, it is the single work whose merits as a creative product cannot be reasonably assessed by an educated layperson. Any literate person can pull a copy of *Republic* or *Hamlet* off the library shelf and obtain at least some understanding of the logical argument or dramatic development. Likewise, anyone can look at a print of the *Last Supper* or listen to a recording of the *Fifth Symphony* and obtain a good notion of what was being graphically conveyed or musically expressed.

In contrast, it would be rare to find a layperson who could make any sense of the *Principia Mathematica*. Even modern mathematicians and physicists find it tough going, given its obsolete notation and presentational style. Worse still, few people these days read Newton's masterwork for either pleasure or edification. It has become a museum piece largely doomed to collect dust on the bookshelf. In comparison, people continue to read the *Republic*, see performances of *Hamlet*, travel to Milan to see the *Last Supper*, and attend concerts showcasing the *Fifth Symphony*. Indeed, it is telling that I refer to da Vinci's painting and Beethoven's composition by their English-language titles, whereas I refer to Newton's treatise by its Latin title instead of the full English translation, the *Mathematical Principles of Natural Philosophy*. These references are merely following conventional practice. Actually, it is customary to cite Newton's work by the terse title *Principia*, rendering it even more cryptic and remote.

Notwithstanding the stark disparity in intelligibility or appreciation, many would argue that Newton's work rates higher than the others in terms of its significance to world civilization. This differential assessment is apparent in the book *The 100: A Ranking of the Most Influential Persons in History* (Hart, 1987). In the author's assessment, Newton placed second, surpassed by Muhammad alone. Shakespeare came in 36th, Plato 40th, and Beethoven 42nd, with da Vinci receiving a mere "honorable mention," having missed the final cut. In fact, once the religious, military, and political leaders are deleted from the top 100, scientists dominate the residual list of creators. These scientists include Albert Einstein (10th), Galileo Galilei (13th), Charles Darwin (17th), Euclid (22nd), Nicolaus Copernicus (24th), Michael Faraday (28th), James Clerk Maxwell (29th), Antoine Laurent Lavoisier (31st), Antony van Leeuwenhoek (39th), Werner Heisenberg (43rd), Alexander Fleming (45th), Max Planck (54th), William Harvey (57th), Antoine Henri Becquerel (58th), Gregor Mendel (59th), Joseph Lister (60th), René Descartes (64th), Edward Jenner (72nd), Wilhelm Conrad Röntgen (73rd), Enrico Fermi (76th), Leonhard Euler (87th), John Dalton (93rd), Johannes Kepler (97th), and Niels Bohr (100th).

Admittedly, anyone can easily challenge these rankings. Perhaps such a single-handed undertaking is inherently presumptuous. I mention this assessment only because it illustrates the common belief that scientific creativity should be held in higher esteem than other forms of creativity. This status is apparent elsewhere besides this ranking. It is evident in the works counted as "books that changed the world," about half of which are scientific rather than literary or philosophical (Downs, 1983). This differential appreciation is also revealed in the much more extensive public support given to scientists compared with artists. In the United States, for example, the budget of the National Science Foundation far exceeds that of the National Endowment for the Arts. The same disparity is seen in the Nobel Prizes, which now are bestowed in four areas of scientific creativity (physics, chemistry, physiology or medicine, and economics) but in solely one domain of artistic creativity (literature). When *Time* magazine decided to pick the person of the century at the close of the millennium, it identified not an artist, nor even a leader, but rather a scientist – namely, Einstein. If *Time* magazine were published at the end of the 17th century, Isaac Newton might have received that honor.

But what does it take to conceive a masterpiece like the *Principia*? One obvious response is simply to affirm that it represents a concrete consequence of *creativity*. To be more precise, the *Principia* should be called a work of *scientific creativity* and thus distinguish this instance of creativity from whatever process produced the *Republic*, *Hamlet*, *Last Supper*, and *Fifth Symphony*. However, this answer really begs the question. What do we mean by scientific creativity? What are its underlying processes? Who has the capacity to produce a work like the *Principia* and who does not? When and where does scientific creativity occur? These issues cannot be addressed without first recognizing that creativity may be viewed from more than one perspective.

FOUR POSSIBLE PERSPECTIVES

Scientific creativity is a topic addressed by many distinct disciplines or what have been termed *metasciences* (Gholson et al., 1989; Simonton, 1988b). The most important of these metasciences are the history of science, the philosophy of science, the sociology of science, and the psychology of science. Not surprisingly, each of these metasciences has a somewhat distinctive outlook on the phenomenon. Part of the disciplinary variation may result simply from contrasts in methodological techniques and substantive interests. Where historians prefer narratives, philosophers favor analyses. While sociologists like to discuss institutions, psychologists like to look at individuals. Nonetheless, some of the differences among the metasciences are also based on the essential fact that scientific creativity can be examined from four principal perspectives: logic, genius, chance, and zeitgeist.

Logic

Philosophers of science have long tried to provide a logical foundation for scientific discovery. These attempts date as far back as Francis Bacon and René Descartes, the former emphasizing inductive reasoning and the latter emphasizing deductive reasoning. To varying degrees, these attempts have attracted great thinkers such as John Locke, Immanuel Kant, and John Stewart Mill. Moreover, the role of logical reasoning is certainly apparent in any high-impact scientific contribution. Newton's *Principia*, for instance, was often taken as a supreme demonstration of the hypothetico-deductive method, a mode of logical analysis that established a paradigm for how best to do science. This view of scientific creativity has the asset of giving science a high degree of incontrovertible inevitability. Provided that the logical deductions fit the empirical facts, it is difficult to challenge scientific truths, and science should continue to accumulate such truths as it extends its methods to all the natural phenomena of the universe.

Some proponents of the psychology of science have adopted the same perspective on scientific creativity (Tweney, Doherty, & Mynatt, 1981). The most conspicuous among these advocates was Herbert Simon, a cognitive psychologist noteworthy for becoming a Nobel laureate in economics. In 1973, Simon published an article in *Philosophy of Science* in which he emphatically argued that scientific discovery betrays a definite logic. This position was based on a general belief that creativity was nothing more than a guise of problem solving, itself a process governed entirely by logical procedures (Newell, Shaw, & Simon, 1958). To strengthen this case, Simon and his colleagues have conducted an impressive number of laboratory experiments and computer simulations that purport to establish the logical underpinnings of scientific discovery (Klahr & Simon, 1999).

Especially provocative are the so-called *discovery programs* (Kulkarni & Simon, 1988; Langley et al., 1987; Shrager & Langley, 1990). These programs claim to replicate the achievements of great scientists by applying logical analyses to empirical data. As if to emphasize the creative prowess of these programs, the software is often named after some big names in the history of science – such as, OCCAM, BACON, GALILEO, GLAUBER, HUYGENS, STAHL, FAHRENHEIT, BLACK, DALTON, PAULI, and GELL-MANN. Of these, BACON may be the most representative. It specializes in the inductive method, yielding data-driven discoveries as advocated in Francis Bacon's *Novum Organum*. By using Baconian induction, BACON reputedly has rediscovered Kepler's Third Law of planetary motion, Black's Law of temperature equilibrium, Ohm's Law of current and resistance, Prout's hypothesis of atomic structure, the Gay–Lussac Law of gaseous reaction, Dulong–Petit Law of atomic heat, and the derivation of atomic weights by Avogadro and Cannizzaro (Bradshaw, Langley, & H. A. Simon, 1983). This impressive list of discoveries appears to make a strong argument for the viewpoint that scientific creativity is the product of mere logic.

Naturally, these simulations often seem to trivialize the achievements of great scientists. If a computer program can duplicate their accomplishments so easily, then it seems like anyone can make significant contributions to science. Nothing really special is required, particularly when computer programs can accomplish in a few seconds what it took real scientists whole careers to achieve. Simon (1973) himself drew this implication. For example, he claimed, "Mendeleev's Periodic Table does not involve a notion of pattern more complex than that required to handle patterned letter sequences" (p. 479). Going beyond mere speculation, Simon even conducted the following informal experiment:

> On eight occasions I have sat down at lunch with colleagues who are good applied mathematicians and said to them: “I have a problem that you can perhaps help me with. I have some very nice data that can be fitted very accurately for large values of the independent variable by an exponential function, but for small values they fit a linear function accurately. Can you suggest a smooth function that will give me a good fit through the whole range?” (H. A. Simon, 1986, p. 7)

Of the eight colleagues, five arrived at a solution in just a few minutes. In ignorance of what Simon was up to, they had independently arrived at Max Planck’s formula for black body radiation – an achievement that earned Planck a Nobel Prize for Physics.

Simon’s stance appears to endorse the seemingly outlandish assertion once made by the philosopher Ortega y Gasset (1932/1957). According to Ortega y Gasset,

> it is necessary to insist upon this extraordinary but undeniable fact: experimental science has progressed thanks in great part to the work of men astoundingly mediocre, and even less than mediocre. That is to say, modern science, the root and symbol of our actual civilization, finds a place for the intellectually commonplace man allows him to work therein with success. (pp. 110 – 111)

Once a scientist masters the logic of science and the substance of a particular discipline, creativity is assured.

Genius

The idea that discovery features such a straightforward logic appears to contradict the idolizing praise often bestowed on scientific genius. Thus, not only is the *Principia* deemed a model scientific contribution, but its author also is often acclaimed in the most grandiose terms. “Nature and Nature’s laws lay hid in night: / God said *Let Newton be!* and all was light,” said the poet Alexander Pope (Cohen & Cohen, 1960, p. 285). More explicitly, mathematician Joseph Louis Lagrange called Newton “the greatest genius that had ever existed” (Jeans, 1942, p. 710). Hence, it should come as no surprise that not everyone accepts the limitations of the logic stance. Opponents include philosophers of science such as Karl Popper (1959) as well as Nobel Prize–winning scientists. For example, Max Planck (1949) held that creative scientists "must have a vivid intuitive imagination, for new ideas are not generated by deduction, but by an artistically creative imagination" (p. 109). Similarly, Albert Einstein reported "to these elementary laws there leads no logical path, but only intuition" (Holton, 1971–72, p. 97).

If these testimonials can be taken on face value, then the proposition that discovery has a logic may have been vastly overstated. Instead, scientific creativity might require some special abilities or traits that set the great scientists apart from their lesser colleagues. Individuals who claim these characteristics to the highest degree may even be called geniuses, or at least potentially so (Simonton, 1999a). This is the position advocated by psychologists who represent a separate tradition within the psychology of science (Feist & Gorman, 1998; Simonton, 1988b). For example, some psychologists believe creativity requires the intellectual and dispositional capacity to generate unusual associations and analogies as well as rich, even dream-like imagery (Mednick, 1962; Rothenberg, 1987; Suler, 1980), a contention that dates as far back as Alexander Bain (1855/1977) and William James (1880). This is not a capacity that can be possessed by everyone but rather belongs to a creative elite. Furthermore, these cognitive processes are more illogical than logical. In effect, those who maintain the genius perspective are arguing that great scientists are precisely those who have the ability to dispense with logic. They can thereby come up with ideas that cannot be derived by inductive or deductive methods alone. This contrast is suggested by the manner in which James (1880) described the mental processes of great thinkers:

> Instead of thoughts of concrete things patiently following one another in a beaten track of habitual suggestion, we have the most abrupt cross-cuts and transitions from one idea to another, the most rarefied abstractions and discriminations, the most unheard of combination of elements, the subtlest associations of analogy; in a word, we seem suddenly introduced into a seething

cauldron of ideas, where everything is fizzling and bobbling about in a state of bewildering activity, where partnerships can be joined or loosened in an instant, treadmill routine is unknown, and the unexpected seems only law. (p. 456)

This description seems a far cry from the linear and discrete logic implemented in the discovery programs.

Chance

If the James (1880) passage has any descriptive validity, then the discovery process might be best described as disorderly, unpredictable, and chaotic. Thoughts tumble over each other willy-nilly, and ideas emerge more by happy accident than by design or deliberation. This implication fits nicely with the third perspective on creativity – the notion that it represents the workings of chance processes. Like the logic and genius perspectives on scientific creativity, this one also has a long history. An early example is the 1896 essay "On the Part Played by Accident in Invention and Discovery" written by the physicist Ernst Mach. Nearly half of a century later Walter Cannon (1940), the physiologist, published a classic article on "The Role of Chance in Discovery." The term that is most frequently applied to these events is *serendipity*, a noun introduced by Horace Walpole in 1754 and defined as "the faculty of making fortunate discoveries by accident" (*American Heritage Electronic Dictionary*, 1992).

Numerous examples of serendipitous events have been documented (Austin, 1978; Roberts, 1989; Shapiro, 1986). Among the more prominent cases are those presented in Table 1.1. Such events often are so unexpected that they can exert an inordinate influence over the course of scientific history, thrusting it in surprising directions (Kantorovich & Ne'eman, 1989). Radioactivity and X-rays provide obvious examples. Serendipity even has a prominent role in the folklore of science. Many schoolchildren have heard the story about how Newton "discovered gravity" after watching an apple fall from a tree.

TABLE 1.1. Some Representative Episodes of Serendipity in the History of Science and Technology

Name	Discovery or Invention	Date
Columbus	New World	1492
Grimaldi	interference of light	1663
Haüy	geometric laws of crystallography	1781
Galvani	animal electricity	1791
Davy	laughing gas anesthesia	1798
Oersted	electromagnetism	1820
Schönbein	ozone	1839
Daguerre	photography (daguerrotype)	1839
Perkin	synthetic coal-tar dyes	1856
Kirchhoff	D-line in the solar spectrum	1859
Nobel	dynamite	1866
Edison	phonograph	1877
Pasteur	vaccination	1878
Fahlberg	saccharin	1879
Röntgen	X-rays	1895
Becquerel	radioactivity	1896
Richet	induced sensitization (anaphylaxis)	1902
Pavlov	classical conditioning	1902
Fleming	penicillin	1928
Dam	vitamin K	1929
Domagk	sulfa drugs (Prontosil)	1932
Plunkett	Teflon	1938
de Maestral	Velcro	1948

Note: Several of the dates are only approximate.

To be more precise, however, serendipity assumes many forms, some of which may be better called instances of *pseudo-serendipity* (Roberts, 1989; Simonton, 1999c). In cases of true serendipity, the discovery was not only accidental but also unintended or undesired (Díaz de Chumaceiro, 1995). The individual discovers something he or she was not even looking for. Alexander Fleming's discovery of the antibacterial properties of *Penicillium* is a prime illustration. On other occasions, a scientist discoverers what he or she was looking for, but manages to do so solely via some unexpected route, and usually not without considerable "trial and error."

Nevertheless, to perceive creativity as a chance phenomenon is not equivalent to claiming that creative scientists are merely "lucky." Because some scientists appear to be consistently more lucky than others, it is probably more correct to assert that scientific genius includes a capacity for the exploitation of chance. As Louis Pasteur famously said, "chance favours only the prepared mind" (Beveridge 1957, p. 46). A portion of that preparation could entail the cognitive and dispositional attributes associated with scientific genius.

Zeitgeist

Although the chance perspective is not necessarily inconsistent with the genius perspective, it is strikingly incompatible with the fourth and last viewpoint on scientific creativity. Sociologists of science have argued that discoveries and inventions are the inevitable product of the sociocultural system – often personified as the *zeitgeist* or "spirit of the times." For instance, Robert K. Merton (1961a) maintained, "discoveries and inventions become virtually inevitable (1) as prerequisite kinds of knowledge accumulate in man's cultural store; (2) as the attention of a sufficient number of investigators is focused on a problem – by emerging social needs, or by developments internal to the particular science, or by both" (p. 306). This position is also maintained by historians of science who believe scientific creativity is contextually determined (Boring, 1963; Furumoto, 1989). This view is especially strong among Marxist historians who hold that scientific ideas must instantaneously and irrevocably reflect the underlying materialistic conditions of the society (Bernal, 1971).

Whether advocated by sociologists or historians, such sociocultural determinism seems antithetical to the very concept of serendipity, pseudo or otherwise. How can a discovery or invention result from pure chance and yet at the same time be completely determined by zeitgeist? But it should be equally apparent that the zeitgeist position is also opposed to the genius perspective (Boring, 1963; Kroeber, 1917; Merton, 1961a). If discoveries and inventions are the inevitable result of sociocultural determinism, then the individual scientist or inventor is reduced to being a mere agent of zeitgeist. As a result, his or her personal characteristics may matter not one iota. For instance, Leslie White (1949), a cultural anthropologist, belittled the very idea that any special talents were required to invent the steamboat. "Is great intelligence required to put one and one – a boat and an engine – together? An ape can do this" (p. 212). One reason why he could make this emphatic claim is that the invention of the steamboat is usually credited to more than one independent inventor. The most frequently named candidates for the honors are Jouffroy, Rumsey, Fitch, and Symington (Kroeber, 1963). If so many distinct individuals could be responsible for the same invention, then it appears more likely that the idea for the steamboat was "in the air" waiting for anyone to pick. The inevitability of the event precluded not just chance but also genius.

Of course, one might argue that this instance is too exceptional to exclude so categorically the other two perspectives. But advocates of sociocultural determinism argue otherwise, compiling dozens, even hundreds of cases (Merton, 1961b; Ogburn & Thomas, 1922). Cases like the steamboat are so commonplace that they have even earned a special name, that of *multiples* (Lamb & Easton, 1984; Merton, 1961b). Notable examples of multiples include the creation of calculus by Newton and Leibniz, the proposal of a theory of evolution by natural selection by Darwin and Wallace, and the discovery of the laws of genetic inheritance by Mendel, De Vries, Correns, and Tschermak. Such examples are taken as incontestable proof of sociocultural determinism. For instance, Alfred Kroeber (1917), another cultural anthropologist, believed it was no mere coincidence that De Vries, Correns, and Tschermak all rediscovered Mendel's laws a few months apart within the same year. On the contrary, Mendelian genetics "was discovered in 1900 because it could have been discovered only then, and because it infallibly must have been discovered then" (p. 199). The individual players in this multiples episode were as extraneous as chance was absent.

THEIR POTENTIAL INTEGRATION

By now it should be obvious that these four viewpoints do not form a coherent account of scientific creativity. The logic position appears to contradict both the chance and genius positions, and the zeitgeist position is opposed to the latter two positions as well. Although the logic viewpoint is not obviously inconsistent with the zeitgeist viewpoint, the two viewpoints are more independent than mutually supportive. Perhaps this hodgepodge of unrelated and incompatible perspectives should be expected. After all, to some degree logic, chance, genius, and zeitgeist reflect deeper intellectual controversies that have been going on for centuries if not millennia. Especially pertinent are age-old debates about the relative prominence of rationality versus irrationality, chance versus determinism, and individual versus society (Simonton, 1976d, 2000b). The discrepancies also may have resulted from the contrasts between separate academic disciplines. It certainly makes sense that sociologists would champion the zeitgeist perspective while psychologists favor the genius perspective. Sociology concerns groups, psychology individuals.

It would be tempting, given these intellectual debates and disciplinary divisions, to just give up and resign ourselves to the inconsistencies among the four perspectives. Maybe scientific creativity is too complex a phenomenon to lend itself to a coherent explanation. Alternatively, we can opt to pick one perspective as the "truth" and arbitrarily reject any other perspective that disagrees with that decision. Yet neither of these choices is attractive from a scientific outlook. It would be the height of irony to propose that scientific creativity cannot be the subject of successful scientific study. Consequently, my goal in this book is to offer a scientific analysis that integrates all four perspectives. This integration is attained by subsuming three of the perspectives under the fourth, giving the latter explanatory primacy. In particular, the logic, genius, and zeitgeist positions are subsumed under the chance position (cf. Simonton, 2003b). Although the former perspectives are subordinated to the latter perspective, the analysis preserves the unquestionable findings generated by each point of view. In other words, the best of the contrary positions are incorporated rather than ignored.

This integration begins in Chapter 2, where I discuss the distinctive features of creative products in the sciences. In Chapter 3, these features are provided a theoretical explanation that highlights the probabilistic nature of scientific creativity. This theoretical explanation is then linked to substantive explanations in Chapter 4, where I discuss the probabilistic consequences of certain prominent aspects of scientific activity. The final two chapters take this explanatory elaboration even further. Chapter 5 discusses creative scientists and Chapter 6 treats scientific discovery. The book closes by consolidating the diverse aspects of this integrated account of creativity in science.

In the end, it should become clear that the scientific creativity that produced *Principia* must be the joint product of logic, chance, genius, and zeitgeist – with chance primus inter pares.