
Scientific
Creativity
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Throughout the preceding exposition of the creation of a specific poem, I have continually asserted that I was presenting an illustrative example. The psychological processes I have described operate generally and universally in creativity and are not merely characteristic of this particular poet's functioning nor of the particular creation of this poem. I must now set about producing evidence for this assertion. To start, I shall shift the focus rather sharply and leap into an activity that seems very remote from the making of poetry. The subject matter is highly technical and impersonal and seems a far cry from the warm and vibrant, intensely personal material considered so far. My concerns here are the subjects of physical science and of the scientific enterprise.

This leap, extreme and hopefully creative in itself, could also turn out to be foolhardy. After all, not only is the subject matter of the physical sciences quite unlike that of the arts but scientific thinking has long been considered the sine qua non of the logical, the objective, and the rational mode. It might hardly seem likely that the emotionally perfused unusual thought processes I have so far described could play an important role in science. Furthermore, unlike the artist, the scientist presumably deals with external and con- sensually verifiable reality. His domain is not subjective or internal reality, nor are characteristically shifting standards of artistic preference and taste applicable to his productions. The scientist is said to *discover* laws that already existed, he does not himself create these laws. There are clear rules for evaluating the validity of scientific laws having nothing whatsoever to do with the scientist's personality, his way of working, nor with the personalities, biases, or tastes of his audience. The law exists in nature, he does not make it and place it there; unlike the artist, he makes nothing new but primarily sees and understands.

All of these distinctions between science and art engender serious reservations about whether identical psychological processes could possibly operate in the two endeavors. Indeed, I myself held such serious reservations for a very long time. Only slowly did I change my mind. Because of a serendipitous finding from my research, I virtually was driven to begin to acknowledge a similarity between artistic and scientific creativity. In a particular experiment designed to assess whether elements of janusian thinking were connected to creativity in a large group of college undergraduates, I divided the entire group into a creative subgroup and a noncreative control subgroup. My criteria for designating the members of the creative group, however, were derived solely on the basis of data I had obtained indicating creativity in the arts. Aside from further matching between the groups on the basis of sex, age, intelligence, and socioeconomic status, I paid no attention to any other information I had about characteristics of the subjects in the two groups. To my surprise, the results of the experiment were equivocal: there was no definite distinction between the subgroups with respect to the factors of janusian thinking tested. Only gradually did it dawn on me that, because of my own reservations about relating artistic and scientific creativity, I had neglected some important data. I had not paid any attention to subject characteristics pertaining to scientific creativity in distinguishing and designating the two subgroups.

After close inspection of information pertaining to such characteristics, I discovered that a large number of scientifically creative subjects had been placed in the "noncreative" control group! Only a few subjects who happened to be creative in science in addition to the arts had already been placed in the creative group. I shall present the details of this experiment later (chap. 7), but a striking discovery was that the results became completely unequivocal when all the data were reassessed and reevaluated after adding the scientific creators to the creative test group. The performance of the artistically and scientifically creative subjects on the experimental task was greatly similar and, statistically, was significantly different from all other subjects in the experiment to a very high degree.

After this influential experience, I began to search for a meaningful way of conceptualizing the creative process in science. It would not be appropriate to consider all accomplishments and discoveries in science to be the result of a creative process. A very large proportion of scientific work consists of the slow accumulation of facts through rigorous observation and experimentation, characteristically, there are carefully reasoned inferences and conclusions, and the application of universal and readily repeatable skills.[1] Little that is comparable to the dramatic bringing-forth-something-out-of-nothing quality characteristic of the creative arts appears. Only the most rudimentary definition of creation, that is, producing or making something of use, properly applies to such routine scientific activity. The same definition also applies to ordinary manufacturing and to successes in routine scientific work. While the word creativity often is applied in just this way—frequently it is used as an honorific term for carrying out a large number of successful experiments and publishing a large number of papers—we are charged with a more exacting definition here. We are interested in understanding a process that yields more than merely useful results and one that is comparable to creative activity in the arts.

I have discussed scientific creativity with numerous colleagues in the physical sciences and they have been virtually unanimous about the following considerations: meaningful criteria for scientific creativity cannot depend solely on the usefulness or potential usefulness of a discovery. Not only must there be more positive value such as an important usefulness or simply a general importance, there must be newness in some sense and, in analogy to artistic creativity, an element of individual accomplishment. Many useful scientific discoveries have come out of a cumulative process involving the collaboration of numerous investigators and the application of standard inductive and deductive procedures. Little comparable to the highly valued production of an individual artist has characteristically been involved. Among my scientific colleagues, the criteria for scientific creation generally considered most valid and most heuristically productive concern the nature of the discovery, its general importance, and the nature of the thought processes responsible for it.

From a philosophical point of view, the matter is highly complicated. One could take the position that all scientific discoveries are creations in the sense that they always result from an interaction between man and nature. Everything known about nature is processed by, and bears the stamp of, the human mind. Consequently, any discovery bears the impressions and the individual elements of the person who first described and formulated it, and of all the subsequent human minds that elaborated it and built upon it. The idea of left and right orientations of substances in the natural world, for example, is a projection onto nature of a human way of organizing and categorizing sides.

Although such a position may be quite feasible, it requires us to understand, as creative activity, virtually all of man's interaction with his environment. On the other hand, one may take the position I mentioned initially that scientific discoveries are not creations because they are in no sense new. Scientists only find and describe the absolute laws and features that were *always* there, always existing beforehand. But then our inquiry into scientific creativity must end before it starts. Finally, one may say that scientific discoveries that are very important, those that change life, society, or the physical environment in some significant way, are creations in that they *bring about* something new. While this last position raises questions about who really does the creating—society, the discoverer, God, or more mundanely the manufacturers and engineers who process and produce discoveries such as penicillin, nuclear energy, and the like—it is essentially the one I shall adopt here. It does not justify an interest in the scientist's thought processes, but neither do the other positions I have mentioned. The focus on thought processes is warranted on the basis of general interest, a general interest derived from certain known similarities between the scientific thinking involved in important discoveries and the thinking involved in artistic creation. So-called intuitive thinking and other types of leaps of thought analogous to what are commonly designated as artistic intuition and inspiration have played a definite role in scientific discovery.

According to my physical scientist colleagues, effective theory building fulfills their criteria and is the sine qua non of scientific creation. First, a theory can always be considered made or created because it never fully corresponds to anything discoverable in nature, at least such correspondence can never be proven. Second, effective theories by definition have far reaching and important consequences. Third, intuitive thought processes always, in some degree, play a role in the development of theories. Limiting scientific creativity only to effective theory building, however, would omit much of what we are looking for in scientific activity. Many scientific discoveries do not consist of general theories, they consist of the discovery of physical facts. As I shall illustrate presently, such facts are often discovered through leaps of thought that are directly analogous to types of thinking we characteristically associate with the creative arts. We must be interested not only in whether the scientist's product or discovery is technically and philosophically worthy of designation as a creation but also in whether he *functions* in a creative fashion in making it. Therefore, our interest is in scientific leaps of thought as well as the development of scientific theories.

Throughout the course of scientific history, leaps of thought and intuitions have been frequently connected to great discoveries. Some of the stories are virtually apocryphal such as the account of Newton's discovery of the law of gravitation while watching an apple fall in his mother's garden,[2] but the autobiographical statements of great scientists amply document the phenomenon. Darwin described his very important flash of intuition as follows:

> In October 1838, that is, fifteen months after I had begun my systematic enquiry, I happened to read for amusement Malthus on *Population,* and being well prepared to appreciate the struggle for existence which everywhere goes on from long continued observation of the habits of animals and plants, *it at once struck* me that under these circumstances favorable variations would tend to be preserved and unfavorable ones to be

> destroyed. The result of this would be the formation of a new species. *Here, then, 1 had at last got a theory by which to work.* [Italics added][3]

Darwin, as we well know, spent the remaining forty-four years of his life proving the hypothesis of natural selection, an hypothesis that came to him all at once as a leap of thought. Clearly, the thought did not emerge fully formed with no antecedent; Darwin stipulates that his previous experience and thought had prepared him well for this sudden understanding. But rather than a carefully reasoned, step-by-step inductive process of deriving inferences on the basis of specific observations and experiments, the idea came to him as a flash of intuition, a flash that waited on his further researches before it could be proven.

Another famous instance of an intuitive leap is described in the oft-quoted testimony of Henri Poincare, the man responsible for some of the most important mathematical discoveries of the latter part of the nineteenth century. The following is his description of the events leading to one of his important discoveries or creations, the mathematical theory involving "Fuchsian functions," a special form of automorphic functions:

> For a fortnight I had been attempting to prove that there could not be any function analogous to what I have since called Fuchsian functions. I was at that time very ignorant. Every day I sat down at my table and spent an hour or two trying a great number of combinations, and I arrived at no result. One night I took some black coffee, contrary to my custom, and was unable to sleep. A host of ideas kept surging in my head; I could almost feel them jostling one another, until two of them coalesced, so to speak, to form a stable combination. When morning came, I had established the existence of one class of Fuchsian geometric series. I had only to verify the results, which only took a few hours.
>
> Then I wished to represent these functions by the quotient of two series. This idea was perfectly conscious and deliberate; I was guided by the analogy with elliptical functions. I asked myself what must be the properties of these series, if they existed, and I succeeded without difficulty in forming the series that I have called Theta-Fuchsian.
>
> At this moment I left Caen, where I was then living, to take part in a geological conference arranged by the School of Mines. The incidents of the journey made me forget my mathematical work. When we arrived at Coutances, we got into a break to go for a drive, and, just as I put my foot on the step, the idea came to me, though nothing in my former thoughts seemed to have prepared me for it, that the transformations I had used to define Fuchsian functions were identical with those of non-Euclidian geometry. I made no verification, and had no time to do so, since I took up the conversation again as soon as I had sat down in the break, but I felt absolute certainty at once. When I got back to Caen I verified the result at my leisure to satisfy my conscience.[4]

In the same speech before the *Societe de Psychologie* in Paris, Poincare went on to ascribe such discoveries, as I mentioned earlier, to the functioning of unconscious processes in scientific creation. Although this was not a completely revolutionary idea at the time, Poincare's talk stimulated another famous mathematician, Jacques Hadamard, to collect and document instances of seemingly unconscious factors operating in his own work and the work of other important mathematical figures. Hadamard's specific description of what he called an "unconsciously" achieved discovery of his own, the discovery of the valuation of a determinant, was as follows:

> I see a schematic diagram: a square of whose sides only the verticals are drawn and inside of it, four points being the vertices of a rectangle and joined by (hardly apparent) diagonals. . . . It . . . seems to me that such was my visualization of the question in 1892 [when I made the discovery] as far as I can recollect.[5]

Many others have emphasized the importance of presumed unconscious factors in other types of scientific discoveries as well.[6] But, irrespective of the type of explanation, whether correctly attributed to unconscious factors or not, the major matter I want to emphasize now is that such leaps of thought or intuitions are highly characteristic of scientific discovery. Typically, as with Poincare, a leap of thought occurs in the course of an investigation, often accompanied by a subjective sense of certainty, and subsequently it is submitted to verification through working out of equations, observation, or experimentation.

Many other testimonies of important scientific discoverers describe the leap of thought followed by verification. Helmholtz, the father of physiological optics and also a great mathematician and philosopher, talked about his discoveries as follows:

> In my papers and memoirs I have not, of course, given the reader an account of my wanderings, but have only described the beaten path along which one may reach the summit without trouble. . . . There are many people of narrow vision who admire themselves greatly if once they have had a good idea—or even think they have had one. An investigator or an artist who is continually having a great number of them is undoubtedly a privileged being and is recognized as a benefactor of humanity. But, who can count or measure such mental flashes? Who can follow the hidden paths by which ideas are connected? . . . As I have often found myself in the unpleasant position of having to wait for useful ideas, I have had some experience as to when and where they come to me which may perhaps be useful to others. They often steal into one's train of thought without their significance being at first understood; afterward some accidental circumstance shows how and under what conditions they originated. Sometimes they are present without or knowing whence they came. In other cases they occur suddenly, without effort, like an inspiration. As far as my experience goes they never come to a tired brain or at a desk.[7]

Other dramatic instances of leaps of thought abound in important scientific discoveries. Pasteur discovered immunology in a moment of sudden understanding; W. B. Cannon's biological theory of the flight-fight syndrome occurred to him during a sleepless night; Carl Friedrich Gauss, the physicist and mathematician, indicated the following in his memoirs: "The law of induction discovered January, 1835, at 7 *a.m.,* before rising." Physicist Enrico Fermi arrived at his major discovery, the method for producing "slow" or "thermal" neutrons, as a result of an idea that came, as he said, "with no advanced warning, no conscious, prior reasoning."[8]

One of the most vivid descriptions of the thinking leading to an important discovery was given by August von Kekulé, the chemist who formulated the ring structure of the benzene molecule. Not only organic chemistry but biochemistry and the modern science of molecular biology are beneficiaries of his contribution. Kekulé arrived at the conception of a ring structure after a sudden visual experience in which a snake seized hold of its own tail. Although the story of this discovery has now become an apocryphal one in which Kekulé is represented as having been drunk or as dreaming at the time, in his original description he stipulated that he was in a state of half-sleep *(Halbschlaf).* Prior to visualizing the snake, the active directed nature of his thinking was, as he described it, as follows: "My mind's eye, sharpened by repeated visions of similar art, distinguished now . . . structures of manifold form."[9]

These examples, some of which I shall discuss in greater detail, all indicate the importance of leaps of thought in scientific discovery. Although Poincare expresses the feeling most explicitly, all of the descriptions indicate a sense of formulation achieved all at once, an idea lacking in clear antecedents and accompanied by a feeling of certainty. From the point of view of the subjective experience of the scientist, then, all of these thoughts are certainly creative. They are experienced as new and discontinuous with previous thoughts and they all have positive value. Initially valuable because sensed as correct and important, their value is verified by more ordinary types of deductive and inductive logical processes.

Unconscious Thought Processes and Scientific Creativity

Myriad examples of such leaps of thought in science are available. I have chosen to cite the particular ones above partly because they are connected to very important, far-reaching discoveries (or, as in the case of Helmholtz, because the person describing the thinking has made such discoveries) and partly because they are examples connected with rather varied subjective states of consciousness. Thus, Kekulé refers to a state of half sleep; Cannon cites a state of sleeplessness in the middle of the night; Poincare also refers to sleeplessness and, along with Helmholtz, he describes a state of relaxed wakefulness as well—the latter, in fact, insists that fatigue is antithetical to leaps of thought; Gauss describes a discovery right after awakening, a time when hypnopompic consciousness is often in full sway.[10] Darwin's and Pasteur's ideas, and presumably Hadamard's, occurred during full consciousness, Darwin while reading, Hadamard while working, and Pasteur while interpreting the results of an experiment.

Theories emphasizing the importance of unconscious factors in scientific creation have been largely influenced by the frequent descriptions of these sudden, subjectively mysterious leaps of thought. Such theories have proposed what seem equally mysterious explanations involving the idea of unconscious "work" going on in the mind of the creator, work that somehow sifts out the unnecessary aspects of his thinking and focuses him on the correct answer. For instance, Wallas's popular theory or description of creative thinking invokes an unclear analogy to physical and biological processes with the use of the word "incubation" to refer to a period of unconscious thinking or unconscious work occurring between preliminary stages of preparation and a stage of illumination or attainment of the correct idea.[11] Theorists unduly influenced by highly dramatic examples such as Kekulé's solution in a supposedly dreamlike state and by descriptions of solutions occurring early in the morning or late at night have assumed these constitute definite evidence for the importance of unconscious work in scientific creativity. The possibility of primary process thinking leading directly to scientific creations and discoveries arises.

The great variation and diversity of states of mind described in the previous examples, however, indicate that neither dreaming nor a markedly altered state of consciousness is necessary for scientific creativity. There is still no reason to postulate an upsurgence of primary process thinking in consciousness. Suddenness and a sharp shift of thinking are described by all and this must be explained, but the proper explanation pertains to the structure of thought processes leading to scientific creations rather than to primary process upsurgence or to the sole operation of a mysterious type of unconscious creative work. Unconscious processes do decidedly play a role in scientific creativity in a manner similar to the role of unconscious processes in art.[12] Janusian and homospatial thinking, the mirror image of dreaming types of thought that both represent and gradually unearth unconscious processes, also operate in scientific discovery.[13]

Two Momentous Scientific Discoveries of the Twentieth Century

I will illustrate the operation of one of the mirror-image processes, janusian thinking, in scientific creation by quoting extended descriptions of the key processes of thought involved in two of the most important scientific discoveries of this century: the discovery of the double helix structure of deoxyribonucleic acid (DNA) by James D. Watson and the formulation of the general theory of relativity by Albert Einstein.

The conception of the macromolecular structure of DNA as chains of smaller molecules (protein bases) oriented in double helical fashion was a momentous one. For some time before that, it had been known that DNA was the chemical substance responsible for the transmission of inherited capacities in living organisms, but the manner of carrying out the transmission was baffling. Many scientists had suspected that the answer to the problem of transmission, the so-called mechanism of genetic coding, lay in the structural qualities of DNA and a good deal of work had been done toward elucidating those qualities. Cumulative knowledge and scientific collaboration helped produce the solution. But the person who made the actual discovery, the person who conceived the specific double helical structure, was the young microbiologist, James D. Watson.[14] Fortunately, Watson has documented enough details about the discovery to make it possible to trace the thought processes involved. That he did not simply follow a step-by-step type of logical process but that the solution came as a leap of thought, fully comparable to the other creative leaps we have discussed, is clearly documented in his description.

In his book, *The Double Helix,* Dr. Watson describes a long period of evaluating various approaches and following hunches about the best way to proceed. Finally, he settled on collecting data provided by X-ray crystallography. Working on a wire model of the structure, he and Francis Crick carefully and logically assessed information from various sources and tried many alternative possibilities. While a good deal of careful logic, methodological judgment, and even luck played a role in his search, the key step of the discovery came as follows:

> When I got to our still empty office the following morning, I quickly cleared away the papers from my desk top so that I would have a large flat surface on which to form pairs of bases held together by hydrogen bonds. Though I initially went back to my like-with-like [the bases adenine with adenine, guanine with guanine,

> thymine with thymine, cytosine with cytosine] prejudices, I saw all too well that they led nowhere. When Jerry [Donohue] came in I looked up, saw that it was not Francis [Crick], and began shifting the bases in and out of various other pairing possibilities. Suddenly I became aware that an adenine-thymine pair held together by two hydrogen bonds was identical in shape to a guanine-cytosine pair held together by at least two hydrogen bonds. All the hydrogen bonds seemed to form naturally; no fudging was required to make the two types of base pairs identical in shape. . . .
>
> The hydrogen bonding requirement meant that adenine would always pair with thymine, while guanine could pair only with cytosine. Chargaff's rules [adenine equals thymine, guanine equals cytosine] then stood out as a consequence of a double-helical structure for DNA. Even more exciting, this type of double helix suggested a replication scheme much more satisfactory than my briefly considered like-with-like pairing. Always pairing adenine with thymine and guanine with cytosine meant that the base sequences of the two intertwined chains were complementary to each other. Given the base sequence of one chain, that of its partner was automatically determined. Conceptually, it was thus very easy to visualize how a single chain could be the template for the synthesis of a chain with the complementary sequence.
>
> Upon his arrival Francis did not get more than halfway through the door before I let loose that the answer to everything was in our hands. Though as a matter of principle he maintained skepticism for a few moments, the similarly shaped A-T [adenine- thymine] and G-C [guanine-cytosine] pairs had their expected impact. His quickly pushing the bases together in a number of ways did not reveal any other way to satisfy Chargaff's rules. A few minutes later *he spotted the fact* that the two glycosidic bonds (joining base and sugar) of each base pair were systematically related by a diad axis perpendicular to the helical axis. *Thus, both pairs could be flip-flopped over and still have their glycosidic bonds facing in the same direction. This had the important consequence that a given chain could contain both purines and pyrimidines at the same time, it strongly suggested that the backbones of the two chains must run in opposite directions.*
>
> The question then became whether the A-T and G-C pairs would easily fit the backbone configuration devised during the previous two weeks. At first glance this looked like a good bet since I had left free in the center a large vacant area for the bases. However, we both knew that we would not be home until a complete model was built in which all the stereochemical contacts were satisfactory. There was also the obvious fact that the implications of its existence were far too important to risk crying wolf. Thus I felt slightly queasy when at lunch Francis winged into the Eagle [restaurant] to tell everyone within hearing distance that we had found the secret of life. [Italics added][15]

Compared to the descriptions of mental events connected with the creation of the poem in the earlier sections of this book, these passages are probably even more difficult to follow, especially if one is not familiar with the biochemical issues involved. Several points, however, emerge clearly from the description to give us an understanding of the nature of his thought processes. First, he had arrived at a conceptual formulation of a particular double helical structure all at once; much remained to be done to test his conception and establish its feasibility. Second, although he describes "shifting the bases in and out of various other pairing possibilities" in somewhat trial and error fashion, the conceptual formulation was not merely a proposal for pairing, it was not merely a conception of the means by which the chemicals were joined together in accordance with the previous findings by Chargaff. I have italicized the sentences (second paragraph here) indicating that the specific conception was of a complementary spatial structure rather than of a like-with-like pairing; he conceived of the structure of a double helix as explaining the mechanism of genetic replication. As his colleague Crick only later came to see, Watson's complete conceptual formulation (also in italics) of the double helix was of a spatial structure having two identical sequences of chemicals running in opposite directions. Watson says that Crick "spotted the fact," meaning that he, Watson, knew it already. His discovery, then, was due to a janusian thought: Watson *conceived that the chains* were *identical and opposite at the same time.* The structure of DNA, it may be said, existed in nature, but it required janusian thinking to recognize it.

The discovery of the very important mechanism of genetic replication, then, was the result of a leap of thought, a creative one, and the leap involved janusian thinking. Embedded as this discovery was in a process of collecting information from various sources, the primarily inductive process at most stages of the search, as well as the headlong race toward breaking the genetic code among many leading scientists of the time, it may seem hard in retrospect to see the creative leap and Watson's unique contribution. Wouldn't someone else have discovered this double helix if Watson hadn't (with Crick's important help)? Wasn't the discovery of the double helix only the uncovering of a fact of nature, a fact that could have been uncovered by other means? Could the structure have been discovered without conceiving the simultaneous opposition? All these questions may be posed and speculated about, but no speculation would alter the story of the actual discovery, Watson's arriving at the solution in just the manner he did. He shifted all at once from the idea of like-with-like pairing to the concept of simultaneous opposition.

Another enormously important twentieth-century discovery in the natural sciences also occurred by means of a leap of thought. This was the discovery, the formulation, to be more exact, of the general theory of relativity by Albert Einstein. For persons living in this day and age, I need hardly spell out, at any length, the significance of this particular theory for science and for the ethos of our time. As a new theory of gravitation, it embraced Newton's classic theory as a special case. Not only did nuclear explosives and power become possible because of this theory, but many of the major developments in modem physics, astronomy, and allied fields are a direct result of it. Our current knowledge of the nature of the physical universe depends significantly on it.

Virtually all scientific theories and discoveries are, as Helmholtz said in the quotation above, presented in a logical, sequential form when they are published. Seldom, if ever, does the scientist reveal the actual thoughts helping him to arrive at his solution (psychologists understandably do so more than others). Einstein was no exception; he presented the general theory of relativity in the manner best calculated to prove its efficacy and feasibility. Recently, however, Einstein's actual thoughts leading to the theory have come to light in an unpublished essay written by him in approximately 1919. The essay was discovered by Gerald Holton among other Einstein papers being collected for posthumous publication by Princeton University Press.[16]

Prior to the development of a general theory of relativity, Einstein had presented what is now called the special principle of relativity. While the special principle was the initial formulation, the later general theory, of course, had more widespread implications. The essay was written in Einstein's own hand, and entitled by him, "The Fundamental Idea of General Relativity in Its Original Form." Although some of it will again be difficult for the nontechnical reader, I will quote a large section of it and then return to discuss specific parts:

> In the development of special relativity theory, a thought—not previously mentioned—concerning Faraday's work on electromagnetic induction played for me a leading role.
>
> According to Faraday, when a magnet is in relative motion with respect to a conducting circuit, an electric current is induced in the latter. It is all the same whether the magnet moves or the conductor; only the relative motion counts, according to the Maxwell-Lorentz theory. However, the theoretical interpretation of the phenomenon in these two cases is quite different:
>
> If it is the magnet that moves, there exists in space a magnetic field that changes with time and which, according to Maxwell, generates closed lines of electric force—that is, a physically real electric field; this electric field sets in motion movable electric masses [that is, electrons] within the conductor.
>
> However, if the magnet is at rest and the conducting circuit moves, no electric field is generated; the current arises in the conductor because the electric bodies being carried along with the conductor experience on electromotive force, as established hypothetically by Lorentz, on account of their (mechanically enforced) motion relative to the magnetic field.
>
> The thought that one is dealing here with two fundamentally different cases was, for me, unbearable *[wai mir unertrdglich].* The difference between these two cases could not be a real difference, but rather, in my conviction, could be only a difference in the choice of a reference point. Judged from the magnet there certainly were no electric fields, judged from the conducting circuit there certainly was one. The existence of an electric field was therefore a relative one, depending on the state of motion of the coordinate system being used, and a kind of objective reality could be granted only to the electric and magnetic field together, quite apart from the state of relative motion of the observer or the coordinate system. The phenomenon of the electromagnetic induction forced me to postulate the (special) relativity principle.

> When, in the year 1907, I was working on a summary essay concerning the special theory of relativity for the *Yearbook for Radioactivity and Electronics* I tried to modify Newton's theory of gravitation in such a way that it would fit into the theory. Attempts in this direction showed the possibility of carrying out this enterprise, but they did not satisfy me because they had to be supported by hypotheses without physical basis. At that point there came to me the happiest thought of my life, in the following form:
>
> Just as in the case where an electric field is produced by electromagnetic induction, the gravitational field similarly has only a relative existence. *Thus, for an observer in free fall from the roof of a house there exists, during his fall, no gravitational field* [italics Einstein's]—at least not in his immediate vicinity. If the observer releases any objects, they will remain, relative to him, in a state of rest, or in a state of uniform motion, independent of their particular chemical and physical nature. (In this consideration one must naturally neglect air resistance.) The observer is therefore justified in considering his state as one of "rest."
>
> The extraordinarily curious, empirical law that all bodies in the same gravitational field fall with the same acceleration immediately took on, through this consideration, a deep physical meaning. . . . The fact, known from experience, that acceleration in free fall is independent of the material is therefore a mighty argument that the postulate of relativity is to be extended to coordinate systems that are moving non-uniformly relative to one another.[17]

These passages by Einstein are fascinating not only because they indicate that a janusian formulation of simultaneous antithesis, simultaneous motion and rest, played a key role in a generally unquestioned piece of scientific creation—both a leap of thought and the development of a theory—but because they help clarify the specific functioning of the mirror-image janusian process in scientific creativity. I will return to the essay as quoted to clarify the points I have just made.

In the first four paragraphs, Einstein spells out, in strictly logical terms, the specific theoretical problem initially attracting his attention. He shows his deep familiarity with the information and principles of the scientific area of his concern. In science, as in art, we must take for granted that the creative thinker has an excellent, if not exceptional, grasp of the technical aspects of his field.[18] As I stated previously with respect to Darwin and others, much preparation is required before creative leaps of thought occur. An additional factor is demonstrated in the material of these paragraphs; Einstein not only knows the field exceptionally well but he recognizes an important problem in it. Such recognition, some would say, is the crux of scientific creativity. To define crucial problems in a field, they assert, requires extraordinary ability; once a crucial problem is clearly and fully defined, methods can be found to solve it. While I would not disagree about the importance of recognizing crucial problems, I suspect that such overemphasis on this aspect of the process is based on an assumption that scientific problem solving is always logical in a straightforward and standard way. In view of what we have assessed so far, such an assumption clearly is not warranted.

Although I cannot at present provide an explanation for Einstein's recognition of the problem posed by the Faraday and Maxwell-Lorentz theories,[19] draw attention to the phrase Einstein uses to describe his orientation to the problem: in the first sentence of the fifth paragraph, he says, "The thought that one is dealing here with two fundamentally different cases was, for me, unbearable." What have we here? This is hardly a cold, logical, objective approach to a scientific problem. Is it then Einstein's use of literary license? In other words, was he merely speaking figuratively and exaggerating for its dramatic effect?

In the light of other information we have about Einstein's position on scientific questions, notably his stormy rejection of quantum theory on the basis that he found it emotionally unsatisfactory,[20] it is unlikely that he was speaking figuratively. He is here expressing a strong emotional position about a scientific problem. Could we call this emotional position an aesthetic feeling? Surely. But to call it aesthetic should not, after the earlier discussion in this book, stop our search for other psychological factors in the emotion. The point I am leading to is that Einstein's strong statement of emotion at this juncture must be taken seriously. Why might he have felt so strongly about whether two fundamentally different cases were involved? Certainly in the absence of more detailed psychological information about Einstein—information about how and under what circumstances he be- became acquainted with these theories, his associations about the sentence in question, and other material one would want for an adequate psychological assessment—we cannot precisely say what factors were involved. But we certainly should have reason to suspect that the conceptual problem involved particular emotional and unconscious concerns. On the basis of accumulated clinical knowledge from psychoanalysis and on the basis of recent trends in cognition research indicating strong connections between cognition and motivation, there is reason to believe that such emotional and unconscious correlates help to dictate a scientist's interest in a problem and even the particular way he initially defines and structures such a problem.[21]

Following the assertion of his strong emotional position on the matter, Einstein goes on to spell out the tight logic leading to his postulation of the first, special, relativity theory. Although he does not mention it here, Einstein's first presentation of his postulate in 1905 contained, of course, highly technical and elaborate extensions of this logic, a logic stated with great simplicity in this passage. As with the creative process in the arts, therefore, we see an emotionally laden idea subjected to rigorous unraveling and development, a development that depends on the requirements of the discipline. For Einstein, it is deductive logic and mathematical exegesis, for the poet, it is expressive verbalization, unification, metaphorization, etc. Because we lack data from this account about the specific unconscious factors in Einstein's emotionally charged position or about the actual cognitive steps he followed in the deductive and mathematical process, we should not assume that Einstein's unraveling and development was markedly different from the poet's. For instance, many leaps of thought and many types of affects may have accompanied the working out of the first special relativity principle.

My observations up to this juncture do not, of course, indicate the operation of a mirror image of dreaming process in Einstein's creativity. They merely lend plausibility to the possibility of such an emotion-driven operation. But now we come to the key aspect of the testimony—the leap of thought enabling him to extend the first relativity principle into the general theory of relativity. This is the idea Einstein called "the happiest thought of my life." We must now look at this aspect of the testimony very closely because the idea itself is quite complex.

The sixth paragraph begins with the connective phrase, "Just as in the case." This phrase is of interest because it indicates the introduction of an analogy. I bring this up, not because I am attempting to perform a close linguistic analysis here, but because analogy and so-called analogic thinking has been widely considered to be a hallmark of creative thought. And indeed, Einstein states directly, in the previous paragraph, that he was looking for an analogy in nature that would allow him to bring Newton's theory of gravitation into the theory of relativity, the step making it a general theory. There is no doubt, I think, that analogic thinking—the search for, and discovery of analogies—is a crucial part of creative thinking just as it is a crucial part of all effective thinking. Analogic thinking is a specific type of logical thinking and it can occur in stepwise fashion—careful and systematic consideration of one related analog after another—or it can occur within a creative leap of thought. In other words, although analogic thinking plays a role in creativity, sometimes a prominent one, it is not the determinant aspect of it.

Looking then at Einstein's arrival at the particular idea he called "the happiest thought" of his life, we see that he has discovered the particular analogy he sought. The *form* of the particular analogy, however, is distinctive: it is highly illogical and contradictory on the surface, but it contains a deep and important logic and rationality. He says, *"Thus, for an observer in free fall from the roof of a house, there* *exists, during his fall, no gravitational field."* This is the thought Einstein himself italicized. And what, on the surface, could be more antithetical and illogical? Imbued, as everyone was in the year 1907 and as nonphysicists still are today, to think of gravity and falling as motion—intense motion for that matter—how could there be both falling and no falling, the effects of gravity and no effects, and how could there be both motion and rest simultaneously? For Einstein emphatically indicates here that the "observer" in free fall is *both in motion and at rest at the same time.*

Immediately, Einstein tells us how. He explains the transcendent logic of the thought because he is fully aware of the apparent contradiction at the time he poses the complex solution. He explains how the fact of the observer both in motion and at rest simultaneously pertains to the larger principle of general relativity. Dramatically, this principle was confirmed through data collected during the solar eclipse of 1919. There is little doubt from the account recorded here that Einstein was fully rational and fully conscious at the moment that his "happiest thought" was formulated.

This concept of the observer in the opposite states of motion and at rest simultaneously is a definite instance of a janusian formulation, and the account indicates steps in the janusian process. Einstein's development of the general theory of relativity, as here described, resulted from a process that was the mirror image of dreaming. Both the presence of the janusian formulation and Einstein's statement of the emotional importance he attached to the problem outline a thought process in this creative sequence having direct analogies with the poetic creative sequence described earlier. Einstein, like the poet, seems to have been struggling with a problem having both intellectual and emotional roots, both conscious and unconscious aspects, and mirror-image-of-dreaming processes played a crucial role in the solution. What unconscious factors might have been incorporated in the janusian thought are totally a matter of speculation. The specification of someone falling from "the roof of a house" catches the psychologically speculative eye. Why such a definite image? What was in Einstein's Unconscious at the time?[22] All suggestive questions, to be sure, but forever speculations.[23]

Now, armed with this detailed specification of thought sequences by Watson and by Einstein and the documentation of the crucial role of janusian thinking in both these instances of scientific creation, I shall turn back to some of the important examples of supposedly unconsciously generated flashes of scientific intuition I cited earlier. A close examination of these examples will, I think, show the ubiquity of the mirror-image processes in diverse types of creation.

Mirror-Image Processes in Scientific Creation

Darwin's conception of the evolution of species and his formulation of the key notion of natural selection certainly ranks among the most important scientific achievements of all time. To be sure, Darwin's greatness does not inhere solely in the formulation itself but largely also in his intensive and extensive observation and documentation of supporting evidence. Let us look again at his description of the circumstances under which the specific leap of thought, the creative theoretical leap, occurred. After a long time of searching for the appropriate formulation (at least four years according to his autobiography),[24] he states, "I happened to read for amusement Mai thus on *Population,"* and then a few sentences later, "it at once struck me. . . .”

The fact that Darwin was reading Malthus when he finally hit on the idea of natural selection has always suggested something rather strange and paradoxical. The main point of Malthus's thesis is that untrammeled human population growth relative to a fixed environment would result in *extermination of the species* because of competition for existence. And yet we see Darwin postulating that this struggle for existence results in the enhancement and perfection of the species relative to its environment!

What does this tell us about Darwin's thinking? By no means am I the first to recognize this apparent contradiction in the momentous event. Several generations of scholars have noted it and, in passing, have concluded that Darwin completely misunderstood Malthus's point and took his own meaning from what he read. But is this conclusion really plausible? After reading all of Malthus's detailed descriptions of the negative effects of population growth, is it likely that a man of Darwin's enormous intellect would completely miss the point? It is seriously doubtful. Darwin nowhere disagreed with or contradicted Malthus's point. More plausible, therefore, is the postulate that Darwin's specific idea at that moment was a formulation of *the simultaneous operation of maladaptation and adaptation in the struggle for existence.* He accepted and understood Malthus's point that the struggle for existence could lead to devastating destruction of the species but thought that it also led to adaptive selection. As the Darwin scholar Gruber put it, in summing up the overall impact of the idea, "natural selection, although it might work against maladaptive variants, could also work in favor of occasional variants which were better adapted than their ancestors to the prevailing conditions under which they must survive."[25] Regardless of the particular content of the plausible exegesis of the idea, the structure of the conception is that of simultaneous antithesis, maladaptive together with adaptive, and a manifestation of janusian thinking.

Of additional interest is the fact that Malthus was also in the mind of A. R. Wallace at the time he formulated an idea of natural selection, independently and quite a bit after Darwin.[26] Wallace describes his thinking as follows: "in my case it was his [Malthus's] elaborate account of the action of 'preventive checks' in keeping down the population of savage races to a tolerably fixed but scanty number. This had strongly impressed me, and it suddenly flashed upon me that all animals are necessarily thus kept down —'the struggle for existence'—while *variations,* on which I was always thinking, must necessarily often be *beneficial,* and would then cause those varieties to increase while the injurious variations diminished."[27] Since Wallace patently did not misunderstand Malthus and since he also explicitly thought of the simultaneous oppositions of increase/diminution and beneficial/injurious, it seems clear that the discovery of natural selection required a janusian formulation in order to be made.

The testimonies by Poincare and by Hadamard indicate the operation in creative scientific thought of homospatial thinking. Poincare's account is rich and perhaps overly suggestive, but aside from emphasizing the spontaneous emergence of his thoughts, he provides us, in one place, with a specific description of their nature. He says "A host of ideas kept surging in my head; I could almost feel them *jostling one another, until two of them coalesced* [*s'accrochassent*], so to speak, to form a stable combination."[28] The phrase I italicize denotes a mental image of numerous discrete entities, the represented content of particular ideas, all occupying the same space. He speaks of ideas jostling one another and therefore being represented in some physical spatial form. He speaks of coalescing, and clearly suggests merging and superimposition (see fig. 3A).

Hadamard's discovery of the valuation of a determinant also demonstrates the operation of homospatial thinking, the active conception of two or more discrete entities occupying the same space. The schematic diagram he saw in his mind's eye consisted of a rectangle superimposed on, or occupying the same space as, a square. That the conception involved the same diffuse type of mental image as previously described for the poet's homospatial conception (the horse alone and the horse with a rider) is indicated by Hadamard's reference to "hardly apparent diagonals joining the four points of the rectangle." Conceiving a square, a rectangle, and diagonal lines all occupying the same space requires the type of diffuse image in which certain aspects are hardly apparent (see fig. 3B).

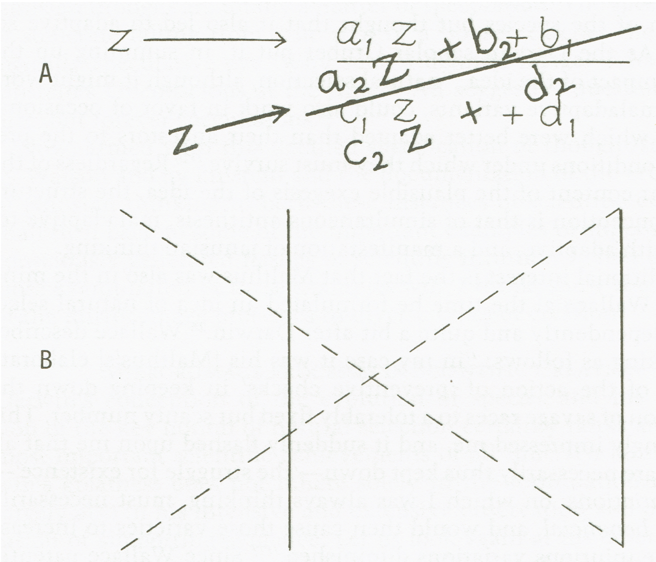

Fig. 3.
Homospatial Conceptions. A. "Ideas . .. coalesce." Diagrammatic conception of Poincare's description of his mental experiences leading to his creation of the Fuchsian functions. (Actual formulas used here pertain to the Fuchsian functions, but they are not intended to indicate the particular content of Poincare's idea, a content he never specifies.) B. "A schematic diagram: a square of whose sides only the verticals are drawn and inside of it, four points being the vertices of a rectangle and joined by (hardly apparent) diagonals.. . . " Representation of Hadamard's conception leading to the creation of the valuation of a determinant. (Diagonals drawn to suggest an image that is impossible to present physically. The rectangle is superimposed upon the square; therefore, the mental image consists of diagonals within the area of the square, not, as drawn here, ending in an extrapolated spatial location.)

Other instances of homospatial and janusian thinking in scientific creation can be inferred from documented circumstances in which scientists have merely described the outcome of their leaps of thought and have not provided enough information about the content of their thinking to enable us to know for certain. Cannon's all-at-once formulation (during a sleepless night) of the flight-fight syndrome, an aroused physiological state of preparedness produced by secretion of the hormone adrenalin, connotes that he conceived the behavioral opposites of flight and fight at the same time. Fermi's spontaneous decision to place a piece of paraffin in the path of propelled neutrons produced slow neutrons which, to everyone's amazement, were more effective in bombarding an atomic nucleus than fast neutrons. As it had previously been assumed that fast neutrons had greater force, it is rather likely that, at the moment Fermi made his decision, he conceived of a neutron having simultaneously antithetical physical properties of having greater projectile power and moving at a diminished speed. In addition to these probable instances of janusian thinking in scientific discovery, the circumstances of James Watt's arriving at the key solution for the design of the steam engine suggests an instance of homospatial thinking. Watt describes the idea occurring on a Sunday walk through a green with an old washing house where Glasgow girls boiled and washed their clothes every day but Sunday, the Sabbath. It was a green near his home where he very frequently walked. His account is as follows: "I had gone to take a walk on a fine Sabbath afternoon. I had entered the Green by the gate at the foot of Charlotte Street —had passed the old washing house. *I was thinking upon the engine at the time,* and had gone as far as the Herd's-house, when the idea came into my mind, that as steam was an elastic body it would rush into a vacuum, and if communication was made between the cylinder and an exhausted vessel, it would rush into it, and might there be condensed without cooling the cylinder" [italics mine].[29] This idea of a separate cylinder was the basis of the condenser, the key step in Watt's development of the steam engine. Inasmuch as Watt made a point of mentioning the washing house, it is highly likely that he had an image of the familiar but absent washing girls in his mind's eye as he passed that point. Since the girls characteristically washed their clothes in steaming kail pots, standing both together and *separately,* it is also reasonable to assume that he had superimposed mental images of his steam engine apparatus ("I was thinking upon the engine at the time") onto images of the girls washing (see fig. 4). The articulation of the critical idea of steam in separate containers, then, followed when he arrived at the Herd's-house. This idea, obvious as it may seem in this day of complete familiarity with condensers and engines, was a culminating link in a general search for such uses of steam of at least a hundred years duration.[30]

Fig. 4.
Artist's conception of the homospatial image leading to the creation of the steam condenser: Watt mentally visualized the girls doing laundry in their kail pots and, superimposing the cylinders upon them, he thought of steam in separate containers. Drawing by Robert C. Morris.

A similar type of mental event led Eduard Benedictus, the French chemist, to the creation of shatterproof safety glass.[31] Benedictus describes having a flask in his laboratory drop ten feet to the floor without breaking or shattering. Noting only that the liquids inside had evaporated and that there was a layer of celluloid enamel inside, he thought no more about the incident until some time later. After dinner one evening, he was thinking about two recent automobile accidents in each of which a young girl had her throat cut and was killed by broken glass. Reflecting on these, he described visualizing the following: "the image of my flask appeared superimposed [se *supeiposa],* in the pale outline of an 'over-impression' upon the constantly changing backdrop of life." Following this image of the flask superimposed on images of the girls and of the accident scenes, he went to his laboratory where he worked until dawn on "a plan which I proceeded to execute, point by point. By evening of the following day, the first sheet of Triplex glass was created." The serendipitous event of a flask falling on the laboratory floor led to a very practical and valuable application through Benedictus's use of homospatial thinking and through further elaboration.

I will end this chapter by focusing on a scientific creator whose thinking characteristically shifted to opposite orientations, an overall pattern related to and generative of janusian thinking. Louis Pasteur, whose discoveries redounded to the everlasting benefit of mankind, approached both theoretical and experimental problems by adopting opposite conceptual orientations, either in fairly short succession or with a dogged persistence.[32] For instance, he devoted a large part of the final years of his life collecting experimental evidence for his cosmological theory that matter originally arose from life rather than, as scientists generally believe, life arose from matter.

Pasteur's first scientific triumph, the discovery of the stereochemical structure of the tartrates—a discovery he never tired of talking about —involved a janusian formulation at an early phase. Given his predilection for opposites, it is no surprise that he early chose a scientific area centrally involving polarity and mirror images. In a lecture delivered before the Societe Chimique in Paris, he described his work on the crystalline structure of tartaric acid and of paratartaric acid and their salts as follows:

> I was a student at the Ecole Normale Superieure, from 1843 to 1846. Chance made me read in the school library a note of the learned crystallographer, Mitscherlich, related to two salts: the tartrate and the paratartrate of sodium and ammonium. I meditated for a long time upon this note; it disturbed my schoolboy thoughts. I could not understand that two substances could be as similar as claimed by Mitscherlich, without being completely identical [Mitscherlich had discovered that the tartrates and para- tartrates had the same chemical composition, the same crystal shape with the same angles, the same specific gravity, the same double refraction, but the solution of the tartrate rotated the plane of polarization, while the paratartrate was inactive]. . . . Hardly graduated from the Ecole Normale, I planned . . . studying . . . tartaric acid and its salts, as well as paratartaric acid. . . .
>
> I soon recognized that... tartaric acid and all its combinations exhibit asymmetric forms. Individually, each of these forms of tartaric acid gave a mirror image which was not superposable upon the substance itself. On the contrary, I could not find anything of the sort in paratartaric acid or its salts.
>
> Suddenly, I was seized by a great emotion. I had always kept in mind the profound surprise caused in me by Mitscherlich's note on the tartrate and paratartrate of sodium and ammonium. Despite the extreme thoroughness of their study, Mitscherlich, as well as M. de la Provostaye [a physicist who published an extensive crystallographic study of these substances], will have failed to notice that the tartrate is asymmetric, as it must be; nor will they have seen that the paratartrate is not asymmetric, which is also very likely. Immediately, and with a feverish ardor, I prepared . . . ,[33]

Pasteur goes on in this account to describe first a disappointment in the outcome of his testing of the hypothesis and then a reassessment of the results by orienting the crystals with reference to a plane perpendicular to the observer; after some other interpretation and exploration, that reassessment provided the answer to the problem.

The ultimate solution to the problem was that paratartaric acid consisted of equal measures of two *opposite light-rotating forms of tartaric acid,* a solution requiring the janusian conception of opposites operating simultaneously. This janusian conception was presaged by Pasteur's earlier hunch which was also a janusian formulation. In attempting to explain Mitscherlich's observations, he had postulated that the reason the two acids shared so many chemical properties was that they were identical but opposite in structure with respect to asymmetry. This formulation, which first led him to an apparently negative result, ultimately produced the correct one and, in its broad outlines, was valid. Pasteur described the overall finding as follows: "the molecular arrangement of the two tartaric acids are asymmetric and, on the other hand, . . . these arrangements are absolutely identical, excepting that they exhibit asymmetry in opposite directions. ... When this ... molecular asymmetry appears in two opposed forms, then the chemical properties of the identical but optically opposite substances are exactly the same, from which it follows that this type of contrast and analogy does not interfere with the ordinary play of the chemical affinities."[34]

Although Pasteur and others subsequently found that the principle just propounded did not always hold absolutely true, his discovery had a great impact on crystallographic research and on the knowledge about levo and dextro rotation that is so taken for granted today. As we know, Pasteur went on from these early researches to make other very important discoveries. One of the most far-reaching of these was his discovery or creation of the science of immunology. Also the result of a leap of thought, the foundation for this discovery or creation was an immediate interpretation of a chance event. In view of Pasteur's famous aphorism, "La chance se favoree preparee" (chance favors the prepared mind), the account is of especial interest, because the circumstances illustrate the type of preparation and thinking involved.

In eighteenth-century England, Edward Jenner began the practice of using an injection of cowpox to protect human beings against virulent smallpox. Supposedly, he was led to this idea by a milkmaid patient who, he thought, was suffering from smallpox. When he told her his diagnosis, she said, "I cannot take the smallpox because I have had the cowpox." Jenner was impressed and began to study the phenomenon systematically; finally, he convinced himself that cow- pox did prevent smallpox infection and he introduced the practice of using injections of the markedly milder infection throughout England and elsewhere in the world. Neither Jenner himself nor any of his enthusiastic followers, however, understood the mechanism of protection nor did they apply the idea to other diseases.

It was Louis Pasteur who discovered the mechanism and the wide applicability of the immunological principle connected to it. Here is the account of the circumstances of his discovery given by Rene Dubos:

> Pasteur had begun experiments on chicken cholera in the spring of 1879, but an unexpected difficulty interrupted the work after the summer vacation. The cultures of the chicken cholera bacillus that had been kept in the laboratory during the summer failed to produce disease when inoculated into chickens in the early autumn. A new virulent culture was obtained from a natural outbreak, and it was inoculated into new animals, as well as into the chickens which had resisted the old cultures. The new animals, just brought from the market, succumbed to the infection in the customary length of time, thus showing that the fresh culture was very active. But to everyone's astonishment, and the astonishment of Pasteur himself, almost all the other chickens survived the infection. According to the accounts left by one of his collaborators Pasteur remained silent for a minute, then exclaimed as if he had seen a vision, "Don't you see that these animals have been vaccinated !"[35]

Hence, in a flash, Pasteur coined a word which connected this event to Jenner's use of cowpox (Latin: *vacca,* "cow") and discovered the mechanism and the principle of immunization.

This story, like so many of the accounts of a creative scientist's leap of thought tends, on first reading, merely to emphasize the mysterious and presumably automatic nature of genius. Such an emphasis contributes to widely held beliefs, described earlier in this chapter, that unconscious factors are directly responsible for such creative leaps. After all, the circumstances suggest that the idea was not merely a matter of inductive thinking, carefully weighing alternatives and drawing logical inferences, nor merely a matter of being prepared to understand the astonishing event because of knowledge of the germ theory of disease. All of Pasteur's colleagues were witnesses to the same event, and it is known that several of them were excellent inductive thinkers and all certainly were thoroughly knowledgeable about the germ theory of the disease, but none of them could explain what happened nor did any formulate the general principle as Pasteur did. Some mysterious factor, "unconscious" work, would seem to have been involved. A careful analysis of the structure of the idea, however, reveals instead that it was an instance of janusian thinking. It appeared mysterious and astonishing partly because it involved the immediate conception of a simultaneous antithesis, a frequently surprising type of conception. It was not merely a matter of some undefined type of superior generalizing ability, nor of grasping remote analogies. In seeing the unexpected event of the chickens' survival as a manifestation of a principle, in seeing its connection to Jenner's practice of injecting cowpox to prevent smallpox, Pasteur needed to formulate the concept that the *surviving animals were both diseased and not-diseased at the same time.* His leap of thought consisted of realizing that the animals that had previously not shown any effects from the culture had nevertheless been affected and diseased in some way; this prior undetected infection had therefore kept them free from disease and protected them against further infection. Fully accepted now, the simultaneously antithetical idea that disease could function to prevent disease was the original basis for the science of immunology.

In spelling out the operation of the mirror-image processes in scientific creativity, I have done a good deal of reevaluating and reassessing many accounts of scientific discovery which do not necessarily reveal the processes on first inspection. Indeed, some of these accounts have been interpreted in totally different ways by previous investigators.[36] This should not be surprising nor, on that account, dismissible. If scientists or interpreters of scientific thinking paid attention to the aspects of thought we are considering here, the processes I am describing would have been discovered long ago. That the processes described are not merely hypothetical constructs without reference to creative scientific thinking today is dispelled by the following two accounts. (1) A Nobel-laureate microbiologist who was a research subject of mine arrived at a new idea about enzyme behavior in 1974 by *visualizing himself superimposed upon an atom in an enzyme molecule,* a homospatial conception. (2) Richard Feynman, the Nobel-laureate physicist, described the following janusian formulation to an interviewer: *"an electron and a positron are the same particle, reversed in time."*[37]

Notes

1 Pertinent to this discussion is the fairly recent proposition advanced by T. S. Kuhn in *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press, 1970) that science advances through the development of paradigms. Kuhn distinguishes between normal scientists and those who develop paradigms producing revolutionary advances. Normal scientists follow paradigms until they are no longer productive or heuristic; at that point, a new paradigm is produced and normal scientists proceed to test it out and apply it. While I am not specifically concerned with formulations about scientific progress here, Kuhn's account of the making of scientific paradigms roughly parallels the concept of creativity in science outlined in these pages.

2 Though it has become somewhat fashionable to doubt the authenticity of the apple story, two of Newton's contemporaries, Pemberton and Stukeley, both report that the first idea occurred while Newton was sitting alone in the garden; see H. Pemberton, *A View of Sir Isaac Newton's Philosophy* (Dublin, 1728). Stukeley's famous account is as follows: "After dinner, the weather being warm, we went into the garden and drank thea, under the shade of some appletrees, only he and myself. Amidst other discourse, he told me, he was just in the situation, as when formerly, the notion of gravitation came into his mind. It was occasion'd by the fall of an apple, as he sat in a contemplative mood. Why should that apple always descend perpendicularly to the ground, thought he to him self. Why should it not go sideways or upwards, but constantly to the earths centre? Assuredly, the reason is, that the earth draws it . . ." (W. Stukeley, *Memoirs of Sir Isaac Newton's Life,* 1752 [London: Taylor &. Francis, 1936], pp. 19-20).

3 F. Darwin, ed., *The Autobiography of Charles Darwin and Selected Letters* (New York: Dover, 1958), pp. 42-43 (repr. of 1892 ed.).

4 Poincare, *Science and Method,* pp. 52-53.

5 J. Hadamard, *The Psychology of Invention in the Mathematical Field* (Princeton, N.J.: Princeton University Press, 1949), p. 81.

6 See numerous examples presented in the following: Montmasson, *Invention and the Unconscious;* Koestler, *Act of Creation;* R. M. Harding, *An Anatomy of Inspiration* (Cambridge: W. Heffer & Sons, 1940); Wallas, *Art of Thought.*

7 H. von Helmholtz, "An Autobiographical Sketch (1891)," in *Selected Writings of Hermann von Helmholtz,* ed. R. Kahl (Middletown, Conn.: Wesleyan University Press, 1971), p. 474.

8 R. Dubos, *Pasteur and Modern Science* (Garden City, N.Y.: Anchor Books, Doubleday, 1960), p. 114; Cannon, *Way of an Investigator,* pp. 59-60; C. F. Gauss, *Works,* vol. 5 (Gottingen: W. F. Kaestner, 1863-1933), p. 609; reported by S. Chandrasekhar in E. Fermi, *Collected Papers* (Chicago: University of Chicago Press, 1965), 2:927.

9 "Mein geistiges Auge, durch wiederholte Gesichte ahnlicher Art ges- charft, unterschied jetzt . . . von mannigfacher Gestaltung" (A. Kekule, *Berichte der Deutsche Chemische Gesellschaft* [1809], 23:1306 [above translated by Meredith Nunes; see n. 13 below for the entire passage]).

10 "Hypnopompic" refers to the semiconscious state preceding awakening; "hypnagogic" refers to a similar state prior to falling asleep. Visual imagery frequently occurs in both states.

11 Wallas, Art of Thought.

12 Of course, we must remember that unconscious factors play a role in all thinking. Here we are discussing the heightened influence or activity of unconscious processes characteristic of all creative thinking.

13 In Japp's initial translation of the lecture (F. R. Japp, "Kekule Memorial Lecture/' in *Memorial Lectures Delivered before the Chemical Society;* also listed as: W. H. Perkins, ed., *Chemical Society Memorial Lectures, 1893-1900* [London: Gurney & Jackson, 1901], pp. 97-169) in which Kekule described his discovery, the word *Halbschlaf* is given as "a doze." The following is Kekule's entire original account in German:

> Da sass ich und schrieb an meinem Lehrbuch; aber es ging nicht recht; mein Geist war bei anderen Dingen. Ich drehte den Stuhl nach dem Kamin and versank in Halbschlaf. Wieder gaukelten die Atome vor meinen Augen. Kleinere Gruppen hielten sich diesmal bescheiden im Hintergrund. Mein geistiges Auge, durch wiederholte Gesichte ahnlicher Art gescharft, unterschied jetzt grossere Gebilde von mannigfacher Gestaltung. Lange

Reihen, vielfach dichter zusammengefiigt; Alles in Bewegung, schlangenartig sich windend und drehend. Und siehe, was war das? Eine der Schlangen erfasste den eigenen Schwanz and hohnisch wirbelte das Gebilde vor meinen Augen. Wie durch einen Blitzstrahl erwachte ich; auch diesmal verbrachte ich den Rest der Nacht um die Consequenzen der Hypothese auszuarbeiten.

Lernen wir traumen, meine Herren, dann finden wir vielleicht die Wahrheit:

"Und wer nicht denkt,

Dem wird sie geschenkt,

Er hat sie ohne Sorgen"

aber hiiten wir uns, unsere Traume zu veroffentlichen, ehe sie durch den wachenden Verstand gepriift worden sind. [Kekule, *Berichte,* pp. 1306-7.]

Although Kekule does use the German world for dream, *Traum,* in his comments to his colleagues about the event as follows, "Let us dream, gentlemen," the full context of his remarks is seldom cited and includes: "take care not to make our dreams known before they have been worked through by the wakened understanding" (translations by Meredith Nunes). He may therefore have been using the word *Traum* in a figurative sense to connote free and daring thinking. As for the actual description of the content of his thought, the following passage indicates a homospatial process whereby two discrete entities are superimposed or fused and occupy the same space: "My mind's eye, sharpened by repeated visions of similar art, distinguished now greater structures of manifold form: long rows, sometimes more closely fitted together, all twining and turning in snake-like motion. But look! What was that? One of the snakes seized hold of its own tail, and the whole form whirled mockingly before my eyes (trans. by F. R. Japp, modified by M. Nunes)."

The atoms are first visualized as strung out in twisting and twining rows with a snakelike *quality.* Immediately following that, a snake is visualized as seizing its own tail. The context makes clear that he saw both the atoms in rows and a snake as occupying the same space because, after describing the snake's action, he says that a single "whole form" ("conformation" per Japp) whirled before his eyes. In his mind's eye ("my mental eye" per Japp), he visualized a snake and rows of atoms together and soon he had articulated a new identity, the structure of the benzene molecule.

A janusian formulation also contributed to the creative result. The circular structure of the benzene molecule was derived from the snake seizing its own tail. As a snake can only seize with its mouth, opposite aspects of the snake, head and tail, were present simultaneously in the initial conception. As I have stated previously, homospatial and janusian thinking often operate conjointly to produce creations. Although we cannot be certain, because of the ambiguity about Kekule's state of consciousness, whether the process consisted only of a mirror image of dreaming or whether there was also an element of dreaming itself, the key cognitions took the form of homospatial and janusian conceptions.

14 For an interesting history and an extensive documentation of the numerous contributors to the ultimate solution, see R. Olby, *The Path to the Double Helix* (Seattle: University of Washington Press, 1974). Although the book clearly reveals that Watson, like all other creative scientists, stood on the shoulders of gaints, it is important to note that Olby's account does not differ from Watson's on any salient point.

15 J. D. Watson, *The Double Helix* (New York: Atheneum, 1968), pp. 125-26.

16 This essay came to my attention long after I discovered janusian thinking and other processes in literary creativity.

17 A. Einstein, "The Fundamental Idea of General Relativity in Its Original Form" (circa 1919, trans. by Gerald Ffolton), manuscript, Einstein Archives, Institute for Advanced Study, Princeton, N.J.; acknowledgment to Otto Nathan, Trustee of the Estate of Albert Einstein, and to Helen Dukas for permission to quote this essay, and to Professor Holton for permission to use his translation. Holton has published other portions and versions of the above translation in *Thematic Origins of Scientific Thought: Kepler to Einstein* (Cambridge, Mass.: Harvard University Press, 1973), pp. 363-64; and "Finding Favor with the Angel of the Lord: Notes Toward the Psychobio- graphical Study of Scientific Genius," in *The Interaction Between Science and Philosophy,* ed. Y. Elkana (New York: Humanities Press, 1975), pp. 369-71.

18 Kris, together with Abraham Kaplan, uses the term "stringencies" to apply to the possible modes of dealing with a problem; clearly, there are quite a large number of such stringencies in science in comparison with art. The creative scientist must be aware of and capable of applying all, or most, of the appropriate stringencies; E. Kris and A. Kaplan, "Aesthetic Ambiguity," in Kris, *Psychoanalytic Explorations,* pp. 243-72.

19 An interesting suggestion, and an observation completely coordinate with the analysis I am presenting here, is to be found in an analysis by Gerald Holton, the Einstein scholar. Holton points out the existence of polarities in Einstein's personality and cites both his sensitivity to polarities in science and his talent for dealing with antitheses. Einstein's interest in the polarity between the Faraday and Maxwell-Lorentz theories, according to this, was an instance of his special sensitivity to such types of problems. Holton's observations are quite fruitful and are especially gratifying because they were arrived at independently,- they were not published at the time I first described janusian thinking (G. Holton, "On Trying to Understand Scientific Genius," *American Scholar* 41 [1971] :95—110).

20"I shall never believe that God plays dice with the world," he said; quoted in P. Frank, *Einstein: His Life and Times,* trans. G. Rosen (New York: Knopf, 1947), p. 208. One can respect this as a religious belief, but certainly it is also a strongly emotional "nonobjective" position for a man of science.

21 Routinely, in psychoanalytic treatment, scientists and other intellectuals reveal the emotional and unconscious roots of their interest in a particular research area and a particular type of conceptual problem. Moreover, applied psychoanalytic research on creative people frequently gives plausible evidence of such connections; see Rothenberg and Greenberg, *Index: Creative Men and*

Women, for bibliographic references. For an interesting attempt at arriving at some of the unconscious bases of Newton's thought, see F. E. Manuel, A *Portrait of Sir Isaac Newton* (Cambridge, Mass.: Harvard University Press, 1968). For references to cognition and motivation research) see chap. 3, n. 5, above.

22 Sidney Blatt suggested to me that Einstein's thinking of the idea of falling from a roof could have represented an unconscious suicide wish. It could also have represented an unconscious wish to fly. A wish to fly often represents a deeper wish for free and uninhibited sexuality and sexual gratification.

23 Einstein's description of a person falling from the roof of a house suggests a homospatial conception along with a janusian one. It is well known that Einstein's thinking was highly visual in nature,- he reported that himself; see Hadamard, *Psychology of Invention,* pp. 142-43, and Wertheimer, *Productive Thinking.*

24 Darwin, Descent of Man, p. 41.

25 H. Gruber and P. H. Barrett, *Darwin on Man* (New York: Dutton, 1974), p. 105. This is an excellent analysis which correctly discusses scientific creative thinking as a sequence of processes rather than a single act. The author of the theoretical section (Gruber) recognizes the overall thrust of Darwin's idea, but misses the factor of simultaneous antithesis.

26 Darwin, nevertheless, accorded Wallace full acknowledgment.

27 "Letter by A. R. Wallace to A. Newton, 1887," in F. Darwin, *Autobiography,* p. 200.

28 The translation of the passage here by Maitland is later than Halsted's frequently quoted one (H. Poincare, *The Foundations of Science,* trans. G. B. Halsted [New York: Science Press, 1913], p. 387). The reflexive verb form *s'accrocher* that Poincare himself used (*Science et Methode* [Paris: Flam- marion, 1924], pp. 50-51) is literally translated as "to fasten together as in crocheting." The Maitland rendition here of "coalesce" seems more appropriate than Halsted's previous one of "collide." The only questionable aspect of Poincare's statement, questionable with respect to being a description of homospatial thinking, is his use of the word *combinaison,* i.e., "combination." New identities or integrations of previously discrete entities result from homospatial thinking, while "combinations" are additive results. Whether the discrepancy is significant or whether Poincare was following common usage and referring broadly to a bringing together that would include either or both combination and integration cannot, unfortunately, be ascertained.

29 Quoted by R. Hart, "Reminiscences of James Watt," in *Transactions of the Glasgow Archeological Society* (Glasgow: James MacNab, 1868), 1:4.

30 For an account of this history, see R. H. Thurston, *A History of the Growth of the Steam Engine* (Ithaca, N.Y.: Cornell University Press, 1939).

31 E. Benedictus, "Les Origines du verre Triplex," *Glaces et Venes* 201 (1930) :9-10; phrases quoted from this article were translated by Brenda Casey.

32 This type of thinking was also characteristic of Sigmund Freud, see A. Rothenberg and W. Sledge, "The Creative Thinking of Sigmund Freud" (in preparation).

33 Quoted in R. Dubos, *Louis Pasteur: Free Lance of Science* (Boston: Little, Brown, 1950), pp. 95-96.

34 Ibid., pp. 99-100.

35 Dubos, *Pasteur and Modem Science,* pp. 113-14. The collaborator mentioned was Pasteur's nephew, Adrien Loir, who, as an early teacher

of Rene Dubos, conveyed the story to him (personal letter from Dubos, July 9, 1975).

36 See aspects of Koestler's, Montmasson's, Harding's, and Hadamard's interpretations: Koestler, *Act of Creation;* Montmasson, *Invention and the Unconscious;* R. M. Harding, *Towards a Law of Creative Thought* (London: Kegan, Paul, Trench, Trubner Co., 1936), esp. the account of James Watt, pp. 140-44; Hadamard, *Psychology of Invention.*

37 R. Feynman, interviews by C. Weiner, 1966-1977; Oral History Collection, American Institute of Physics, New York, N.Y., p. 259.