VISUAL THINKING: THE ART OF IMAGINING REALITY

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> *I'm very dubious about how much any of our ordinary experience is verbalized, but there is no doubt at all that very little of the scientific experience is verbalized. The more one thinks of it, the more certain that seems to be. Well, of course that makes it very hard to put the actual scientific process into verbal terms. You have to find a sort of analogy for it, not a direct representation.*
>
> C. P. Snow[1]

In 1878, a young chemistry professor who indulged liberally in writing poetry and sketching gave his inaugural lecture at the newly founded University of Amsterdam on the subject, "Imagination in Science."[2] The young man's name was J. H. van't Hoff. He defined imagination as "the ability to visualize [mentally] any object with all its properties so that one recognized it with the same great certainty as by simple observation." Facts, he said elsewhere, are the foundation of scientific inquiry, but "Imagination [is] the building material; the Hypothesis, the ground plan to be tested; Truth or Reality, the building. . . ."[3] He, himself, had imagined, when only twenty-two years old, that a possible explanation of the observed facts of carbon compounds might be that the valences of the carbon atom lay at the vertices of a tetrahedron.[4] Hermann Kolbe, a well-known German chemist, immediately seized upon van't Hoff's hypothesis as an example of the flights of fancy that were (in his opinion) bringing contemporary science to ruin.[5] No one can see atoms, said Kolbe, so it is useless to try to imagine what they look like. Science must stick to facts and only to facts. Not surprisingly, Kolbe did just that—he churned out facts—lots of new chemical compounds.[6] He refused to consider whether there might be a common, nonempirical explanation for what he perceived to be individual and unique chemical events. Details rather than ideas were the stuff of science for him. The inaugural lecture at Amsterdam was van't Hoff's chance to reply.

Scientists have always bickered about the relationship between fact and theory and the proper roles of experiment and imagination. Van't Hoff placed imagination above facts. Indeed, he went further, claiming that "imagination plays a role both in the ability to do scientific research as well as in the urge to exploit this capability." This conviction, he continued, combined with his own extrascientific interests, "has prompted me to investigate whether or not this [imaginative] ability also manifests itself in famous scientists in ways other than their researches. A study of more than two hundred biographies showed that this was indeed the case, and in large measure."[7] The most scientifically imaginative scientists, he found, were almost always artists, poets, musicians, and/or writers as well. Furthermore, there appeared to be a correlation between the sort of science produced by a scientist and whether or not he demonstrated nonscientific forms of creativity. As an example, van't Hoff quoted the following comparison by Cuvier of Vauquelin, an eminent but noncreative chemist, and Sir Humphry Davy, a chemist who studied art and wrote poetry good enough to be praised by Coleridge[8]:

> Notwithstanding his innumerable investigations and in spite of the important and noteworthy observations with which Vauquelin enlarged the stock of scientific knowledge, he cannot be considered of the same caliber as Davy. The former put his name in the paragraphs; the latter in the titles of each chapter. In a completely unpretentious manner, the former observed with a lantern the smallest obscurities and penetrated into the darkest nooks; the latter ascended like an eagle and illuminated the large realm of physics and chemistry with a shining beacon.[9]

"I make these words my own," van't Hoff concluded, "in order to describe what research is without imagination, and what it can be if one uses it in an admissible manner."[10] This was his answer to Kolbe. He would be a Davy. Kolbe could be a Vauquelin.

Van't Hoff delivered his inaugural address at the age of twenty-six. During the next ten years, he collaborated with Svante Arrhenius and Wilhelm Ostwald to found the new science of physical chemistry, contributing the fundamental mathematical and thermodynamical bases for the field.[11] One cannot help but note that the simplicity and economy of his mathematical derivations rival those of his poems.[12] One also cannot help but note that, while Kolbe did indeed follow Vauquelin into the nooks and crannies of chemistry, van't Hoff soared after Davy, taking aloft a beacon that illuminated vast new fields of many sciences from physics to geology, in consequence of which he was awarded the first Nobel Prize in Chemistry in 1901. And, in spite of Kolbe, the existence of the tetrahedral carbon atom has since been verified by x-ray crystallography, its theory derived from quantum mechanics, and its form reified in modern molecular models. Time vindicated van't Hoff's theory.

But what of van't Hoff's ideas concerning scientific creativity? The parallel between the imaginative, creative scientific styles of van't Hoff and Davy, on the one hand, and the factually based, detailed studies of Kolbe and Vauquelin, on the other, raises some interesting questions for modern investigators. Is there some basis for the correlation observed by van't Hoff between scientific imagination and other forms of creativity? Can such a correlation of talents be an index to the sorts of problems a scientist is addressing and the style of research he employs? If so, what is the significance of such correlative talents for understanding scientific creativity and ways to foster it through education?

To begin with, my own study of some 150 scientific biographies has, like van't Hoff's study, yielded a large number of scientists who were creative in other fields (Table 1). Most of these men are recognizable as being among the most fruitful thinkers of their respective scientific disciplines. Even so, the lists are doubtless incomplete, since in many cases the evidence for these nonscientific pursuits has emerged from odd and unexpected places. For example, none of the standard biographies of Louis Pasteur mentions his extraordinary artistic skill, nor do those of Emil du Bois-Reymond, George Washington Carver, or Frederick Banting. One of the problems with a study such as this is that scientists, their biographers, and archivists often eschew the nonscientific aspects of the scientific life as being irrelevant to understanding a person's science. Both van't Hoff's study and the data presented here suggest that traditionally ignored aspects of life may very well be relevant to understanding science. Certainly, a correlation between scientific and nonscientific imagination at least looks plausible. But what might it mean, and how might it come about?

It seems to me that the key to the significance of correlative talents has been forged by Brooke Hindle in his recent book *Emulation and Invention.*[13] Discussing Samuel Morse and Robert Fulton, Hindle demonstrates that the inventiveness of these two men was directly linked to their powers of visual imagination. Both men had been artists before they became inventors. Morse had studied art in Europe and was considered one of the best young American artists of his day before he turned to inventing. Similarly, Fulton was a protégé of the painter Benjamin West prior to embarking on his career as an inventor. Hindle has argued persuasively that the skills necessary to inventing and the process by which each man invented were shaped by and reflect his artistic proclivities.

I believe that Hindle's argument can be extended to creative scientists as well. In most cases, however, the abundance of technical and nontechnical art that characterizes inventor-engineers like Morse and Fulton is lacking. One must argue from fragments of knowledge.

Take Louis Pasteur for example. Up till the age of twenty, Pasteur spent significant time painting, and drawing with both pencil and pastels. After Pasteur's death, a well-known Finnish painter, seeing the paintings and pastels, mourned the loss to French art;[14] and the modern art historian Samuel Edgerton has confirmed that Pasteur could at least have become a good academic artist had he not turned solely to science.[15] But what interests me most about Pasteur's art is that he made his first discovery while looking at the preparation of crystalline tartrates no different from those examined by dozens of his colleagues and mentors.[16] Yet he was the first to see that crystalline tartrates exist not in one form, as they were illustrated in the textbooks of his day, but in *three* forms: right-handed, left-handed, and symmetrical. His recognition of this fact marks the discovery of enantiomers, or mirror-image forms, in chemicals. The striking feature of the discovery is that the crystalline facets defining the asymmetry are so small as to be almost unnoticeable, except to an eye trained as was Pasteur's, to perceive detail. Furthermore, Pasteur did not limit himself to the single factor of asymmetric tartrates: his notebooks show that he immediately extrapolated his observation, imagining a whole series of such mirror-image compounds (many of which he subsequently isolated) and what he called a "cosmic asymmetric force" to bring these compounds into existence.[17] He never found evidence for the force. In terms of understanding Pasteur's scientific creativity, it is also noteworthy that he took the time to turn his observations into models.[18]

Another example is Theodor Boveri, whose nonscientific artwork is said to exist, but which I have yet to locate.[19] Boveri maintained throughout his life that he had intended to become an artist, and often wished that he had done so, except for the financial insecurities of the profession. Instead, he became a biologist who dedicated his life to unraveling the mysteries of the cell and its development. His scientific artwork is notable for two features. First, much of it derives from observations made before the advent of specific stains for cell organelles. Thus, no contemporary camera could have recorded what he drew from his repeated observations. But even more interesting is that, unlike a photograph of the same objects—say, of cells dividing—which represent real, unique instances, Boveri's drawings represent idealizations. All of the "unnecessary" details have been left out of his drawings of cell division. But the decision concerning what is "necessary" and what "unnecessary" involves intellectual "filtering." Clearly, the "eye of his mind" directed what he saw with the "eye of his forehead." As Mel Usselman has recently argued,[20] this ability to idealize results, to see through the mess of real-life observations to what *ought* to be there, is one of the marks of genius. It seems clear to me that one of the reasons that Boveri, rather than his colleagues, was able to make the observations that he did, was due to his training as an artist. Philip Ritterbush, for example, has beautifully illustrated how artistic insight made crucial differences not only in what Boveri saw that Hans Driesch did not, but also in how the two men portrayed what they saw.[21] Boveri had learned early what, perhaps, Driesch and others never learned: that perceiving (that is, the use of the "eye of the mind" to interpret observation) is not the same as seeing (that is, the uninterpreted images on the "eye of the forehead"). This distinction suggests that, in fact, photographs may not be the best form of illustration, since photographs usually record "reality" but do not convey a perception of it. In other words, scientific photographs are observations (raw data); scientific illustrations, perceptions (processed data). Every artist learns early that one cannot draw what one sees. You learn, as Ernst Gombrich has demonstrated so well, visual conventions.[22] It is not enough for the scientist to see; he must also perceive, and be able to record his perceptions. Art provided Boveri with both the perceptual and manipulative tools to undertake his research successfully.

Notably, analysis of Santiago Ramón y Cajal's Nobel prizewinning studies of brain anatomy shows the same characteristics as Boveri's drawings:

TABLE 1.

Scientist-Artists

Edgar Lord Adrian
Emile Argand
Frederick Banting
Sir Charles Bell
Claude Bernard
Wilhelm von Bezold
Theodor Boveri
Sir Lawrence Bragg
Ernst Brücke
George Washington Carver
Baron Cuvier
C. D. Darlington
Emil du Bois-Reymond
Pierre Duhem
Félix Dujardin
Sir Alfred Egerton
Michael Faraday
Sir Alexander Fleming
Otto Frisch
Patrick Geddes
Edwin S. Goodrich
Ernst Haeckel
Charles Henry
John Herschel
Sir Cyril Hinshelwood
Phillipe de la Hire
T. H. Huxley
C. G. Jung
Johannes Kepler
Joseph Jackson Lister
Lord Lister
Otto Loewi
Albert Michelson
H. J. Muller
Wilhelm Ostwald
Louis Pasteur
Santiago Ramón y Cajal
Ogden Rood
Maximilian Salzman
Thomas Young
Robert Williams Wood

Scientist-Photographers

Paul Ehrenfest
John Herschel
Robert Koch
J. C. Maxwell
Wilhelm Ostwald
S. Ramón y Cajal
Sir Henry Roscoe
Wilhelm Schlenk

Scientist-Musicians

Jean le Rond d'Alembert
Joseph Auensbrugger
Georg von Békésy
Louis De Broglie
Albert Einstein
Sir James Jeans
Johannes Kepler
Karl Rudolf Koenig
Ernst Mach
Albert Michelson
Max Planck
Sir Ronald Ross
Max Schultz
Homer W. Smith
Voldemar Voigt

Otto Frisch
Werner Heisenberg
Hermann von Helmholtz
Jacques Monod
Rolf Nevanlinna
Wilhelm Ostwald
Edmund B. Wilson
Thomas Young

Scientist-Composers

Alexander Borodin
William Herschel
Comte de Lacepède
Albert Michelson
Sir Ronald Ross

Scientist-Poets

E. N. da C. Andrade
Jacob Bronowski
Ernst Brücke
George Washington Carver
Sir Humphry Davy
Galileo Galilei
Fritz Haber
J. B. S. Haldane
René-Just Haüy
A. V. Hill
Julian Huxley
J.-J. L. de Lalande
Mikhail V. Lomonosov
Etienne Louis Malus
J. C. Maxwell
Gregor Mendel
Herman Minkowski
Walther Nernst
William Odling
Max von Pettenkofer
Charles Richet
Sir Ronald Ross
Karl F. Schimper
Sir Charles Sherrington
James J. Sylvester
J. H. van't Hoff
Richard Willstätter
Robert Williams Wood

Scientist-Writers (Fiction)

Claude Bernard
J. B. S. Haldane
Antoine Laurent Lavoisier
Siméon-Denis Poisson
Charles Richet
C. P. Snow
Alfred W. Stewart
(alias J. J. Connington)
Leo Szilard
Karl Vogt

Scientists Displaying Miscellaneous Forms of Creativity

Wilhelm von Bezold (weaving)
Calvin Bridges (nonscientific inventions)
J. Willard Gibbs (nonscientific inventions)
Friedrich August Kekulé (architecture)
Sir Henry Roscoe (architecture)
Erwin Schrödinger (weaving)

abstraction, idealization, and deletion of "unnecessary" details.[23] It is relevant that, like Boveri, Ramón y Cajal was a frustrated artist and a successful photographer.[24]

Wilhelm Ostwald, eighth Nobel prizewinner in chemistry, and polymath of the first order, represents a similar case. As a boy, Ostwald dabbled in everything from building his own camera and making his own photographic plates, to fabricating his own fireworks and mixing his own paints. He was a reasonably good artist, and a fine violinist.[25] Indeed, he spent so much time at these extracurricular activities that his college education took an extra two years. His parents, who were paying for his education, were not pleased. What they failed to grasp was that Ostwald had developed the same inventive mental and manipulative skills that had characterized Morse and Fulton, and in much the same way. He was able to visualize mentally new scientific instruments in his mind; to transfer them to paper; and to translate the drawings into working apparatuses. It is probable that Ostwald invented more electrochemical apparatus than any of his contemporaries. A man who recommended changing fields every ten years, Ostwald followed his own advice, and during his fifties turned his love for art into a scientific discipline by inventing a mathematical theory of color addition.[26] His studies involved his childhood hobby of mixing his own paints, the standardization of colors and the production of some of the first standardized color wheels and charts, the invention of gray scales that are so important in photography, and the design of new instruments for color analysis. He also wrote extensively on the practice of art from his scientific perspective,[27] and, like his good friend van't Hoff, stated that "the most important of all the qualities that make up a great thinker is originality, by which I mean the capacity to imagine something before it has been investigated."[28]

James Clerk Maxwell represents a similar history. He loved to sketch, produced important scientific studies of color mixtures, and is credited with taking the first color photograph.[29] Sir Henry Roscoe recalled meeting Maxwell when the latter was a student at Cambridge[30]:

> . . . This young man addressed me in very broad Scotch as follows: "Come and see my devil; I've got a devil." So I went. The floor of his room was covered with sheets of white paper; upon these were drawn a most complicated series of curves; from the ceiling was hung a doubly suspended pendulum, the "bob" of which was a heavy weight ending in a point. On placing the point on one of these curves and releasing the weight, the point followed exactly these singular curves running all over the floor in a most grotesque manner. This was my first introduction to Clerk Maxwell and his "devil."

One cannot help wondering in retrospect whether these "demonic" curves were not the prototypes for Maxwell's famous electromagnetic fields of force. Certainly Maxwell had a tendency to reify abstract concepts. Upon receiving the 1879 papers of J. Willard Gibbs in which Gibbs introduced the concept of phase diagrams, Maxwell immediately made a plaster sculpture of the phase diagram of water and sent Gibbs a copy.[31]

Gibbs himself had been an engineer and inventor, with a number of patents to his name, before he had begun his thermodynamical researches. Although I have so far uncovered no evidence of artistic proclivities, very little is known of his childhood or early education. Gibbs's patents certainly demonstrate his ability to think in visual terms. Indeed, in introducing the phase diagram in 1879 he explicitly stated that the advantage of this mode of presentation, as "clumsy as its expression in words may be, is one which presents a clear image to the eye, and which the mind can readily grasp and retain."[32] Given the virtual inaccessibility of Gibbs's mathematical derivations (even Einstein complained of Gibbs's terseness), it may be significant that the only two scientists to appreciate his results prior to 1895 were the two visually imaginative physicists, Maxwell and Ostwald.[33] It is also interesting to note that Gibbs's 1879 paper presents historians of science with a case of what Gombrich would call a shift in visual conventions. In introducing his entropy-derived phase diagrams, Gibbs stated explicitly that he was rejecting the convention of limiting the coordinates to volume and pressure, as had been the fashion since Watt introduced his indicator diagrams for steam engines at the beginning of the century.[34] Much more research along the lines of Gombrich's studies of visual conventions in art is needed into the role of these sorts of visual and mathematical conventions in science.

Finally, there is the example of Einstein, a man whose entire corpus of work revolves around the visual imagining of thought experiments. We know almost nothing about Einstein's childhood or youth, so that it is again almost impossible to say how he developed his uncanny knack of visualizing imagined worlds; yet there are hints. As a child he loved jigsaw puzzles and would spend hours constructing elaborate edifices out of blocks and cards. By the time he began work at the Zurich patent office, he was clearly comfortable with models and drawings. And even as an adult, he showed an unusual delight in puzzles of all kinds.[35] It is not surprising then to find him writing to Jacques Hadamard, that,[36]

> The words or the language, as they are written or spoken, do not seem to play any role in my mechanism of thought. The psychical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be "voluntarily" reproduced and combined. . . . The above mentioned elements are, in my case, of visual and some of a muscular type. Conventional words or other signs have to be sought for laboriously only in a secondary stage. . . .

Indeed, Richard Feynman and Freeman Dyson have expressed the opinion that "Einstein failed [to produce a unified field theory] because he stopped thinking in concrete physical images [later in his life] and became a manipulator of equations."[37] Theirs may be an overstatement, since no one since has produced a unified field theory either, but their opinion does serve to highlight their own sense of the importance of visual thinking in physics. Indeed, Dyson has written at some length about the inability of Einstein and Ernest Rutherford to comprehend each other's research and linked their differences in research to the same sort of mental differences that separated Davy from Vauquelin, and Kolbe from van't Hoff.[38]

There is a further aspect of visual thinking that Einstein characterized as well. He, himself, attributed his insights to the characteristic of asking the simple sorts of questions only a child would ask.[39] Is there, then, something important about the sort of mind that is willing to play extraordinary games, as did Maxwell; or playing "what if atoms are three-dimensional and look like this," as did van't Hoff; or looking for simple beauty and patterns in nature as did Boveri, Ramón y Cajal, and Ostwald? Perhaps.

Certainly Charles Darwin wrote of experiments in mental visualization throughout his notebooks.[40] Peter Debye once stated that "I can only think in pictures . . . [I] had to use [my] feelings—what did the carbon atom *want* to do?"[41] Robert Wilson, a sculptor in his spare moments, has spoken of inventing high energy particle accelerators by "thinking in terms of a visualized mental model."[42] Jonas Salk has written of what he calls mental "games" in which "I would picture myself as a virus, or as a cancer cell, for example, and try to sense what it was like to be either. I would also imagine myself as an immune system engaged in combating a virus or cancer cell."[43] Similarly, Joshua Lederberg has said that the scientist

> needs the ability to strip to the essential attributes some actor in a process, the ability to imagine oneself *inside* a biological situation; I literally had to be able to think for example, "What would it be like if I were one of the chemical pieces of a bacterial chromosome?" and to try to understand what my environment was, try to know *where* I was, try to know when I was supposed to function in a certain way, and so forth.[44]

Now, clearly, the imaginative skills of the poet- or musician-scientist will differ from those of the artist-scientist, but I believe that the sorts of connections I've made here between art, science, and visual imagination, can also be made between art, science, and other forms of nonverbal thinking. I believe that it is significant that so many mathematically skilled scientists have also been deeply interested in poetry and music. In fact, a few years ago, Siegmund Levarie[45] suggested that certain aspects of music make it a particularly apt form for modeling complex systems in which many events occur in parallel. His is an extremely important point when one realizes that verbal thinking is linear, whereas experience of most kinds is nonlinear and concomitant. Music, then, may be a particularly useful means of training the mind to perceive the ways in which the apparent complexity of an experience (e.g., a Bach fugue or a physiological process) may result from the proper application of simple rules and patterns expressed in tandem.

Aldous Huxley noted a facet of literature, and of poetry in particular, that may provide yet another key to the understanding of possible links between the arts and the mathematical sciences. In his book *Literature and Science,* Huxley suggested that two of the primary concerns of the poet or writer are the exploration of language and its purification; that is to say, experimentation with possible meanings of words and their combinations and the elimination of redundancies, imprecise meanings, and nonsense.[46] While it is a common fallacy to believe that no matter how a scientific idea is stated, it retains the same intent, whereas no word can be changed in a poem without altering its meaning, anyone who can read the language of mathematics is surely aware that theoretical physicists and chemists are searching for the same simplicity, beauty, harmony, precision, and elegance in their language that poets seek in theirs.[47] The theoretician and the poet, then, share the common attributes of exploring a descriptive language and of attempting to purify its meaning and its content.[48]

More, it is often stated that if ten artists or ten poets were given the same scene to paint or to describe, they would paint ten different pictures and compose ten different poems, whereas ten scientists given the same problem to solve would arrive at the same answer.[49] While there are a tremendous number of hidden fallacies in that view of the arts and sciences,[50] there is one of particular importance here, and that is the notion that scientific creativity is objective and therefore styleless. Presumably, if every scientist arrives at the same answer to the same problem by the same route then there can be no room in science for individual expression. Yet anyone who participates in scientific research or who works with scientists is surely aware that scientists *do* have styles of research.[51] Indeed, Ludwig Boltzmann once wrote that,[52]

> Even as a musician can recognize his Mozart, Beethoven, or Schubert after hearing the first few bars, so can a mathematician recognize his Cauchy, Gauss, Jacobi, Helmholtz or Kirchhoff after the first few pages. The French writers reveal themselves by their extreme formal elegance, while the English, especially Maxwell, by their dramatic sense. Who, for example, is not familiar with Maxwell's memoirs on his dynamical theory of gases? . . . The variations of the velocities are, at first, developed majestically: then from one side enters the equations of state: and from the other side, the equations of motion in a central field. Ever higher soars the chaos of formulae. Suddenly, we hear, as from kettle drums, the four beats "Put N = 5." The evil spirit V (the relative velocity of the two molecules) vanishes: and, even as in music a hitherto dominating figure in the bass is suddenly silenced, that which had seemed insuperable has been overcome as if by a stroke of magic. . . . This is not the time to ask why this or that substitution. If you are not swept along with the development, lay aside the paper. Maxwell does not write programme music with explanatory notes. . . . One result after another follows in quick succession till at last, as the unexpected climax, we arrive at the conditions for thermal equilibrium together with the expressions for the transport coefficients. The curtain then falls!

Similarly, Thomas Kuhn has written that even when two or more scientists discover the same result (e.g., the principle of conservation of energy), each arrives at his solution by a different path and expresses his answer in a different form that reflects his style of research. Thus, Kuhn writes that whereas,[53]

> in the ideal case of simultaneous discovery two or more men would announce the same thing at the same time . . . nothing remotely like that happened during the development of conservation of energy . . . no two of our [dozen] men even said the same thing. Until close to the end of the period of discovery, few of their papers have more than fragmentary resemblances retrievable in isolated sentences and paragraphs. . . . A diagram of the overlapping passages in the papers of the pioneers of energy conservation would resemble an unfinished crossword puzzle.

So much for our ten scientists all reaching the same answer by the same objectively correct route.

But how is scientific style developed? Why are some scientists integrators, others diversifiers? Why are some specialists and others generalists? Why do some prefer visual or geometrical thinking and others verbal or analytical reasoning? These are not simple questions, nor can they be expected to have simple answers. I cannot but believe, however, that the phenomenon of "correlative talents" must play an important role in the development and expression of scientific styles. Certainly Ramón y Cajal wrote that,[54]

> For my part, I have always believed that the games of children are an absolutely essential preparation for life; thanks to them the infantile brain hastens its development, receiving, according to the hobbies preferred and the amusements carried on, a definite moral and intellectual stamp upon which the future will largely depend.

Ramón y Cajal, recall, wished to be an artist, but was discouraged by parents who felt that artistic expression was sinful. Not until he became a scientist was he able to satisfy his artistic sensibilities:[55]

> It is an actual fact that, leaving aside the flatteries of self-love, the garden of neurology holds out to the investigator captivating spectacles and incomparable artistic emotions. In it, my aesthetic instincts found full satisfaction at last. Like the entomologist in pursuit of brightly coloured butterflies, my attention hunted, in the flower garden of the gray matter, cells with delicate and elegant forms, the mysterious butterflies of the soul.

Similarly, the Finnish mathematician Rolf Nevanlinna, who was also a concert-caliber violinist and a chairman of the Sibelius Academy, wrote that, "music has been a constant companion throughout my life. In a mysterious way, which I find hard to analyse, it has been a continual accompaniment to my research."[56]

Many other scientists, too, have written about science as a quest for beauty, harmony, and pattern.[57] What, then, is the basis for this mysterious conjunction of the sciences and the arts that seems to characterize creative scientists? Clearly, a great deal of research will be necessary before the phenomenon of "correlative talents" can be considered to be well established, and still more will be necessary to determine to what extent nonscientific skills play a role in scientific creativity and how those skills may be manifested. But it will be particularly interesting to see whether differences in scientific styles of research, as exemplified by the abstract unifying work of a Davy, a van't Hoff or an Einstein, on the one hand, and the concrete diversifying research of a Vauquelin, a Kolbe or a Rutherford, on the other, are always reflected in differences in nonscientific talents in any predictable and understandable way. And, it will be fascinating to determine whether the scientific work of artistic scientists differs in some significant manner from musical scientists and poetical or literary ones, too.

One thing seems certain. Most eminent scientists agree that nonverbal forms of thought are much more important to their work than verbal ones. This observation leads me to propound the following hypothesis. The most influential scientists have always nonverbally imagined a simple, new reality before they have proven its existence through complex logic or produced evidence through complicated experiments. There is a simple reason for this phenomenon. Experiment can confirm or disconfirm the tentative reality that imagination invents, and experiments can suggest the need for the invention of a new reality to account for anomalies to the existing one. But experiment cannot, in and of itself, produce conceptual breakthroughs or be used to explain data. Logic is similarly limited. Indeed, philosophers of science are almost universally agreed that logic can be used to test the coherence of theories and to provide proofs of existing ideas, but logic does not produce the ideas to be tested. One must be able to imagine that which is to be tested and how to test it before one can even begin to employ logical, experimental, and verbal forms of thought. Furthermore, I suggest that this ability to imagine new realities is correlated with what are traditionally thought to be nonscientific skills—skills such as playing, modeling, abstracting, idealizing, harmonizing, analogizing, pattern forming, approximating, extrapolating, and imagining the as yet unseen—in short, skills usually associated with the arts, music, and literature.

Several important implications follow, assuming that the phenomenon of "correlative talents" is accurately portrayed here, and that it bears the sort of relation to scientific creativity that I have suggested.

First, most people seem to consider verbal thought to be the highest or even the only form of thought. For example, Arthur Koestler once wrote that, he "who reverts to the pictorial mode of thought is *regressing* to an older and lower level of the mental hierarchy—as we do every night when we dream, as mental patients do when they regress to infantile fantasies."[58] In consequence of this sort of view, a tremendous amount of energy has been expended by philosophers and linguists (most notably Noam Chomsky and his school) to comprehend the structure of language in the belief that when language is understood, thought will be understood. But I find myself in agreement with Aldous Huxley, who wrote that,[59]

> words are few and can only be arranged in certain conventionally fixed ways; the counterpoint of unique events is infinitely wide and their succession indefinitely long. That the purified language of science, or even the richer purified language of literature should ever be adequate to the givenness of the world and of our experience is, in the nature of things, impossible.

In light of the many examples presented here of eminent scientists skilled in nonverbal forms of thought, a purely linguistic approach to thought seems to me to be misguided. Neither our experience of nature nor our ability to think about it are limited to, or are even mainly confined to verbal forms. Thoughts may, in fact, be translated into language only for communicating. But pictures, music, and other nonverbal forms of thought also communicate and can be manipulated logically. Much more research is needed into these nonverbal forms of thought if we are ever to understand creativity and thinking.

Second, those philosophers who admit that formal logic is unable to address the question of the origin of new scientific ideas (i.e., discoveries and scientific imagination) generally go on to assert (as Popper, Kuhn, Feyerabend, Hanson, and others have done)[60] that the process of discovery is therefore illogical or even (shades of Koestler!) irrational. I disagree. Rather, I prefer the view that formal logic, being a verbal construction, is bounded by internal constraints that make it incapable of fruitfully addressing noninductive and nondeductive processes such as modeling, abstracting, harmonizing, pattern forming, approximating, and imagining the as yet unseen. This fact does not make creative thinking illogical. It simply demonstrates that new, nonverbal forms of logic need to be developed to describe these processes rationally. Thus, it seems to me that visual and other nonverbal forms of thinking proffer to philosophy vast wildernesses in need of exploration.

Third, the idea that there is an "eye of the mind" as well as an "eye of the forehead" suggests some important problems for psychologists. Rudolf Arnheim[61] has long advocated an important role for visual thinking in all areas of psychology, and Howard Gardner[62] has recently reopened the case for "multiple intelligences," i.e., the idea that intelligence is not a single entity, but a composite of relatively discrete faculties such as visual thinking, musical thinking, kinesthetic thinking, etc. Clearly the idea of "correlative talents" is at least generally compatible with both Arnheim's and Gardner's ideas, although it begins to address areas in which both men's work is weak: the problems of explaining imagination, creativity, and genius. If van't Hoff was correct that eminent, creative scientists are usually (if not always) creative in other fields of endeavor, then several conclusions follow. First, creativity may depend (at least to some extent) upon the ability to juxtapose and integrate forms of experience usually categorized as disparate and immiscible. Second, the ability so to juxtapose and integrate disparate forms of experience may depend upon the existence of correlative talents in the individual. In other words, creativity may require the ability to transform one form of experience (e.g., a mathematical problem) into another form (e.g., visual), and then be able to translate the resulting idea into a communicable form (be it a drawing, music, or words). Thus, where Gardner has suggested tests for the different forms of intelligence, I would suggest that tests of the ability to translate and transform *between* forms of intelligence are also necessary. These translatory and transformatory skills may provide an index of the sorts of creativity, or the styles of creativity of which an individual is most capable. Such tests will also be necessary to determine to what extent visual imagination is dependent or independent of the kinesthetic skills of drawing or modeling, harmony upon musical training, etc.

Fourth, the phenomenon of correlative talents may have important implications for education. If, as appears to be the case to so many scientists,

TABLE 2.

Writers Trained in Sciences and Medicine

Honoré de Balzac
Anton Chekov
Samuel Coleridge
A. J. Cronin
Erasmus Darwin
Sir Arthur Conan Doyle
Loren Eiseley
J. W. von Goethe
Lars Gyllensten
Oliver Wendell Holmes
John Keats
Arthur Koestler
Paul de Kruif
W. Somerset Maugham
Giovanni Meli
S. Weir Mitchell
Vladimir Nabokov
Istvan Orkeney
Arthur Schnitzler
Samuel Smiles
Gertrude Stein
August Strindberg
Leo Tolstoy
H. G. Wells
T. H. White
William Carlos Williams

Artists Who Studied Science

Max Bill
André Derain
Eugène Delacroix
M. C. Escher
Félix Fénéon
Camille Pissarro
Lucien Pissarro
Georges Seurat
Paul Signac
David Sutter
Vincent van Gogh

Artistic Writers and Poets

Enid Bagnold
Maurice Baring
George Barker
Max Beerbohm
Arnold Bennett
William Blake
Charlotte Brontë
Emily Brontë
Elizabeth Barrett Browning
John Burroughs
Wilhelm Busch
Lewis Carroll
G. K. Chesterton
Wilkie Collins
Joseph Conrad
Walter Crane
Eugene Field
Ronald Firbank
J. W. von Goethe
Kate Greenaway
Thomas Hardy
Julian Hawthorne
Lafcadio Hearn
David Jones
Rudyard Kipling
Edward Lear
Charles Godfrey Leland
John Masefield
Henry Miller
Sean O'Casey
Isaac Rosenberg
John Ruskin
George Russell
William Sansom
Siegfried Sassoon
Bernard Shaw
Stephen Spender
Alfred Lord Tennyson
William Makepeace Thackeray
Dylan Thomas
Henry David Thoreau
J. R. R. Tolkien
Mark Twain
Denton Welch
H. G. Wells

visual or other nonverbal forms of thought are crucial elements in problem-raising and problem-solving ability, then exclusive educational stress upon verbal and mathematical skills drastically limits the types of problems that students can raise and solve. Indeed, if the comments by Einstein and Ramón y Cajal concerning the importance of play are valid, then exclusive reliance upon book learning is itself misguided. Certainly Ostwald, Maxwell, and Gibbs learned as much (if not more) about nature by exploring it through hobbies such as painting, sculpting, inventing, and building as they did through formal book studies. And, returning to Hindle's study of Morse and Fulton, one sees clearly that the nonverbal skills of the inventor-scientist may best be stimulated by active participation in the arts. Yet in many American high schools and universities, science majors are actively discouraged from participating in arts programs because arts and crafts skills are considered to have no intellectual value. In view of the information integrated in the present essay, one can only rue this narrow-minded, intellectual bigotry that is handicapping the minds of the scientists of tomorrow.

Finally, I want to mention in passing that the concept of "correlative talents" seems to be applicable to nonscientists as well as to scientists. Eminent physicians seem always to be multi-talented.[63] A preliminary investigation into the backgrounds of eminent writers and artists has revealed that a significant number have had scientific or medical training,[64] and a considerable number of writers and poets have been artists as well[65] (Table 2). These observations raise the possibility that much of what has been said here about scientific imagination may also be applicable to the understanding of the nonscientific imagination. If so, a fruitful undertaking might be to investigate the degree to which creative individuals in every discipline are also creative in other fields of endeavor, and whether the attribute of "correlative talents" provides a meaningful basis for understanding the qualitative differences that set off some writers, poets, artists, musicians, and other humanists from their less creative colleagues.[66]

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