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ARTISTIC SCIENTISTS AND SCIENTIFIC ARTISTS: THE LINK BETWEEN POLYMATHY AND CREATIVITY

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The literature comparing artistic and scientific creativity is sparse, perhaps because it is assumed that the arts and sciences are so different as to attract different types of minds, each working in very different ways. As C. P. Snow wrote in his famous essay "The Two Cultures," artists and intellectuals stand at one pole and scientists at the other: "Between the two a gulf of mutual incomprehension—sometimes . . . hostility and dislike, but most of all lack of understanding. . . . Their attitudes are so different that, even on the level of emotion, they can't find much common ground" (Snow, 1964, p. 4). Our purpose here is to argue that Snow's oft-repeated opinion has little substantive basis. Without denying that the *products* of the arts and sciences are different in both aspect and purpose, we nonetheless find that the *processes* used by artists and scientists to forge innovations are extremely similar. In fact, an unexpected proportion of scientists consists of amateur and sometimes even professional artists, and vice versa. Contrary to Snow's two-cultures thesis, the arts and sciences are part of one, common creative culture largely composed of polymathic individuals.

We base our argument on five types of evidence that correlate artistic and scientific creativity. First, successful artists and scientists tend to be polymaths with unusually broad interests and training that transcend disciplinary boundaries. Second, artists and scientists have similar psychological profiles as determined by widely used psychological tests. Third, arts proclivities predict scientific success just as intellectually challenging avocations predict success in all fields. Fourth, scientists and artists often describe their creative work habits in the same ways, using the same language, and draw on common, transdisciplinary mental toolkits that include observing, imaging, abstracting, patterning, body thinking, empathizing, and so forth. Fifth and finally, scientists often state that their art avocation fruitfully informs their vocation; artists often draw explicit sustenance from their scientific interests. The arts have often stimulated scientific discoveries and science has often influenced the nature of artistic creativity.

These observations have broad implications for our understanding of creativity, intelligence, and education. First, they establish a connection between personal or "little c" creativity, which most people experience, and "big C" domain-altering creativity, to which only a handful of people contribute. We contend that the individual producing "big C" creativity in one field more often than not exhibits a polymathic array of "smaller c" creativity in other fields. Learning how to manipulate the creative process in one discipline appears to train the mind to understand the creative process in any discipline. In other words, creative people tend to be generally creative, in the sense of being able to make personal contributions to disparate fields. For most people, these contributions vary widely in novelty and effectiveness. Such individuals may be unpublished amateur poets and Nobel Prize–winning chemists, or Sunday painters and paradigm-altering composers. In extreme cases, however, modern "Renaissance people" make relatively important contributions to several sciences, several arts, or to both. The very fact that individuals can participate in a range of creative vocations and avocations at various levels of novelty and effectiveness suggests to us a general creative intelligence independent of disciplinary or domain-specific boundaries.

Equally important, the five correlations we will explore suggest that the devaluation of the arts and the elimination of arts training from many schools may have significant detrimental effects on creativity across all disciplines. One of the few curricular areas in which students learn to make something of at least limited novelty is in the arts. If practice with the creative process through "little c" creative activities is essential to training people for "big C" creative activities, then limiting or eliminating arts programs must have a broad impact. In particular, because arts and crafts avocations are highly associated with scientific creativity, fostering arts education may be necessary to promote the highest forms of scientific creativity, an opinion expressed by many eminent scientists.

SCIENTISTS AS ARTISTS AND ARTISTS AS SCIENTISTS

Our interest in arts–sciences interactions began as graduate students when we serendipitously encountered a series of famous scientists who had also considered artistic careers or who had practiced the arts at a high level as adults (Root-Bernstein, 1987). One of us subsequently documented more than 400 instances (Root-Bernstein, 1989, pp. 318–327). Here we call attention to only a handful of examples. Louis Pasteur, Frederick Banting, and Santiago Ramon y Cajal were all excellent artists (Jackson, 1943; Ramon y Cajal, 1937; Vallery-Radot, 1987). Sir Humphrey Davy, the founder of modern atomic theory, wrote poetry that was praised by his friend and colleague Coleridge (Davy, 1840). Roald Hoffmann, the man who many chemists believe has brought more order to chemical theory than anyone since Mendeleev and his periodic table, is also a widely published poet and playwright (Djerassi & Hoffmann, 2001; Hoffmann, 1988). C. G. Jung, whose artistic output nearly rivaled his psychoanalytical work, described his art making as "a rite of entry" to his science (Jaffe, 1979, p. 205). Roger Guillemin, the Nobel laureate who isolated the first peptide hormones, is also a painter who has since made a reputation as a professional computer artist (Guillemin, 2002). Virologist and vaccine inventor Hilary Kaprowski, following in the footsteps of astronomer William Herschel and chemist Alexander Borodin, has taken time out from his scientific studies to record his musical compositions (Borodin, 1995; Herschel, 1995; Kaprowski, 1999).

We quickly determined that artists were also polymathic in the arts. Musical talent is so easily found among painters (e.g., Jean Ingres, Paul Klee, and Henri Matisse) that author Henry Miller once remarked, "Every artist worth his salt has his 'violin d'Ingres'" (Hjerter, 1986, frontispiece). In Miller's case, his metaphorical "violin" was painting—a typical avocation for writers (Miller, 1974). Many books have, in fact, illustrated the very strong connections that exist between visual talents and writing, most notably Kathleen Hjerter's *Doubly Gifted: The Author as Visual Artist* (1986) and Lola Szladits's and Harvey Simmonds's *Pen and Brush: The Author as Artist* (1969).

Indeed, if one goes to the Web site of the Nobel Foundation in Sweden, or biographical compendia concerning these laureates in literature, one finds that, although avocational interests are mentioned for only 55 of 98, at least a third had adult (a)vocations in at least one other art and that, most often, a visual art (Table 8.1). Some Nobel Prize–winning writers have also acted or directed theatrical productions, played musical instruments or composed. For many, these passions influenced their writing. For some, these multiple talents have been expressed as dual careers: Rabindranath Tagore composed the music for hundreds of his poems that he set as songs; Derek Walcott and Gao Xingjian have exhibited their paintings professionally; Gunter Grass was a professional sculptor and printmaker; Dario Fo has excelled not only as

TABLE 8.1
Arts Avocations and Vocations of Nobel Laureates in Literature, 1901–2002

Noble prize		Visual arts and sculpture	Music	Drama* and dance
1903	Bjornstjerne Bjornson	/ X?		X
1912	Gerhart Hauptmann	X	X	X
1913	Rabindranath Tagore	X	X	
1915	Romain Rolland	X?	X	
1916	Verner Von Heidenstam	X		
1917	Karl Gjellerup	X	X?	
1922	Jacinto Benavente			X
1923	William Butler Yeats	X		X
1924	Wladyslaw Reymont	X		X
1925	George Bernard Shaw	X	X	
1929	Thomas Mann		X?	
1933	Ivan Bunin	X		
1936	Eugene O'Neill			X
1946	Hermann Hesse	X	X?	
1947	Andre Gide		X	
1948	Thomas Stearns Eliot		X	
1951	Par Lagerkvist	X?		
1953	Winston Churchill	X		
1956	Juan Ramon Jimenez	X		
1957	Albert Camus			X?
1958	Boris Pasternak		X	
1966	Nelly Sachs	X?	X?	/ X
1975	Eugenio Montale	X	X	
1979	Odysseus Elytis	X		
1983	William Golding		X	X
1985	Claude Simon	X		
1986	Wole Soyinka			X
1989	Camilo Jose Cela	X		X
1990	Octavio Paz	X?		
1991	Nadine Gordimer	X		
1992	Derek Walcott	X		
1997	Dario Fo	X	X	X
1998	Jose Saramago	X?		
1999	Gunter Grass	X / X		
2000	Gao Xingjian	X		X

Note. Between 31 and 35 literature laureates had at least one other art avocation or vocation out of a total 98 laureates. No information on nonwriting activities was found for 43 of the laureates. Sources include Pribic (1990); Nobel (2002); and Liukkonen (2002).

*Other than writing, as director, actor.

a dramatist, but also as an actor, director, and stage and costume designer (Nobel, 2002; Liukkonen, 1999).

Composers and choreographers tend to be equally multitalented. Arnold Schoenberg and George Gershwin were excellent amateur painters (Lebrecht, 1984); George Hindemith and Igor Stravinsky (who took lessons from Picasso) sketched; Iannes Xenakis composed architecture as well as music, often borrowing the visual line of his buildings from his scores (Matossian, 1986). The choreographer Merce Cunningham has published a book of drawings (Cunningham, 2001); Rod Rodgers, who often set his experimental dance to unusual music, was also a percussion player, a photographer, and graphics designer (Dunning, 2002). Successful artists of all kinds, like scientists, are often artistic polymaths.

Many artists have been amateur or even professional scientists as well. The French composer Olivier Messiaen, for example, was an amateur ornithologist who incorporated bird song into many of his compositions. George Antheil, whose "Ballet mechanique" revolutionized modern music, was an amateur endocrinologist and inventor who held key electronics patents with actress Hedy Lamarr (Antheil, 1945; Braun, 1997). Cesar Cui and Nicholas Rimsky-Korsakov were trained as engineers. Alexander Borodin earned his living as a chemist. Sir Edward Elgar took out several patents on chemical processes. Camille Saint-Saens was an amateur astronomer. Mikhail Balakirev, Ernest Ansermet, Diana Dabney, and Iannes Xenakis—among many other modern composers—earned advanced degrees in mathematics (Root-Bernstein, 2001). Susan Alexjander has drawn on the science of genetics to inform her latest compositions (Alexander, 1996).

Science avocations and vocations are also prevalent among writers. At least 20 of the 55 Nobel laureates in literature for whom nonwriting interests could be documented trained in, practiced, or otherwise immersed themselves in science, engineering, or mathematics (Table 8.2). Jose Echegaray and Salvatore Quasimodo practiced civil engineering, Echegaray for much of his literary life. Bertrand Russell, who won a Nobel for his philosophical writings, was also a mathematician. Alexander Solzhenitsyn taught math and physics for many years. Elias Canetti took a doctorate in chemistry (Pribic, 1990). Amongst writers outside the Nobel circle, science is also a common enterprise. August Strindberg dabbled in chemistry when he was not painting or taking photographs (Hjerter, 1986). Beatrix Potter, the author of the famous Peter Rabbit stories, was an expert on fungi who first suggested (correctly) that lichens were symbiotic plants (Linden, 1966). Novelist Vladimir Nabokov, employed at the Harvard museum of natural history as a lepidopterist, discovered a rare species of butterfly (Johnson & Coates, 1999). H. G. Wells also took his college degree in science, as has virtually every noteworthy science fiction writer since (Asimov, Greenberg, & Waugh, 1985; Clark, 1989). Similarly, a long list of writers that includes William Carlos Williams, Rabelais, Chekhov, John Keats, Sir Arthur Conan Doyle, A. J. Cronin, and Frank Slaughter have been trained in and have also practiced medicine (Coulehan, 1993; Stone, 1988).

In light of Snow's two-cultures thesis, these artist–scientists and scientist–artists are a surprising lot. And yet, perhaps, not as surprising as all that. The connection between polymath and creativity has certainly been described before, notably by Eliot Dole Hutchinson in 1959: "It is not by accident that

TABLE 8.2
Science and Engineering Training and Interests of Nobel Laureates in Literature, 1901–2002

Nobel prize		School* or university	Career, at some time	Self-study or avocation
1901	Sully Prudhomme	X		X
1904	Jose Echegaray	X	X	
1907	Rudyard Kipling			X?
1911	Maurice Maeterlinck			X
1913	Rabindranath Tagore			X?
1917	Karl Gjellerup			X
1917	Henrik Pontoppidan	X	X	
1927	Henri Bergson	X		X
1939	Frans Eemil Sillanpaa	X		X?
1944	Johannes V. Jensen	X		X
1950	Bertrand Russell	X	X	
1951	Par Lagerkvist	X		
1959	Salvatore Quasimodo	X	X	
1960	Saint-John Perse	X		
1962	John Steinbeck	X		X
1967	Miguel Angel Asturias	X		
1970	Alexander, Solzhenitsyn	X	X	
1976	Saul Bellow	X?		
1981	Elias Canetti	X		
1983	William Golding	X		

Note. Total sample is 18–20 out of 98 recipients, 1901–2002. No information on nonwriting interests found for 43 laureates. Sources include Pribic (1990); Nobel (2002); and Liukkonen (2002).

in the greatest minds professions disappear. . . . Such men are not scientists, artists, musicians when they might just as well have been something else. They are creators" (Hutchinson, 1959, pp. 150–152). Others have made similar remarks. So the question becomes what the polymathy–creativity connection means. In particular, what do sciences and arts, or scientists and artists, share of consequence? What might polymaths tell us about creative thinking?

SCIENTISTS AND ARTISTS SHARE SIMILAR PSYCHOLOGICAL PROFILES

One possible explanation for the correlation between creativity in the arts and sciences is that artists and scientists have similar psychological profiles that are not shared by other professionals. This explanation appears to have merit. The primary investigator of this phenomenon was Bernice Eiduson of the University of California, Los Angeles, who, between 1955 and 1980, explicitly compared a range of responses to psychological tests taken by groups of artists, businessmen, and scientists. Eiduson used four major instruments for investigating the participants' psychological profiles: (a) intensive and extensive interviews concerning themselves, their early development, and their personal history; (b) the Rorschach test; (c) the thematic apperception test; and (d) the Miller analogies test. Results were rated on a CA-L rating scale of 50 items by three independent clinical psychologists who did not know the nature of the study or the participants (Eiduson, 1962, 1966; Eiduson & Bechman, 1973; Root-Bernstein, Bernstein, & Garnier, 1993).

Eiduson found that both the artistic group and the scientific group could be clearly differentiated from the business group, but that the artists and scientists could not be distinguished. Artists for example, tended to have diverse intellectual interests and elaborate fantasies. They were highly responsive to sensory experiences as well, and motivated to find diverse ways to express these experiences. Scientists shared all of these characteristics, whereas business people were intellectually narrow, reality-centered, and uninterested in sensual experiences or ways to express them. Altogether, of the 50 cognitive, emotional, and motivational variables studied, only two statistically significant differences between artists and scientists appeared (scientists were more willing to work in structured situations and were less introspective about sex), whereas 20 statistically significant differences were found between the artists and businessmen and 15 between the scientists and businessmen.

Taking into account the interview material as well, Eiduson concluded as follows:

> On the basis of the clinical experimental data both artists and scientists seem to share the same ways of thinking about and perceiving problems and situations; seem to share many attitudes about what they do, respond to the same motivations, and display some of the same personality attributes. The experimental findings showed that artists and scientists were more alike in their cognitive characteristics than they were in personality features, but in both of these areas the persons who were in creative fields were significantly different from persons who had selected business vocations. Therefore, I feel that this material speaks for a general model of the person who goes into a creative vocation. (Eiduson, 1962, pp. x–xi)

Other investigators have also demonstrated cognitive overlaps between artists and scientists. For instance, numerous studies show that students of science perform significantly better on tests of visual thinking and visual memory than do students of the humanities, students of literature, and, surprisingly, students of the arts (Benbow, 1988; Casey, Winner, Brabeck, & Sulivan, 1990; Helson & Crutchfield, 1970; Hermelin & O'Connor, 1986; Winner & Casey, 1992). In fact, visual and spatial thinking tests are among the few reliable predictors of success in science and engineering (Humphreys, Lubinski, & Yao, 1993). And although Richard Mansfield and Thomas Busse (1981) claim that only a handful of psychological tests have ever shown documented correlations with demonstrated creativity in the sciences, the three that do are based on arts-related material: the Strong vocation interest blank test, the Barron-Welsh art scale, and the mosaic construction test.

On the Strong vocational interest blank test, choosing artist, musician, or author as alternative careers were all positively correlated with being ranked as a creative scientist or engineer. Similarly, creative architects chose physicist, chemist, or psychologist as alternative careers significantly more often than their average peers. As Eiduson's study suggested, choosing business-related preferences such as accountant, production manager, purchasing agent, office man, and salesman were negatively correlated with creativity for both scientists and architects. Similarly, most studies of scientists and mathematicians using the Barron-Welsh art scale and the Mosaic construction test have shown that those identified as creative are more likely to prefer, as artists do, complex and asymmetrical patterns as opposed to symmetrical ones (Mansfield & Busse, 1981). These findings also correlate with an extensive and growing literature on the importance of aesthetic considerations for creative work in science in which some scientists refer explicitly to developing their aesthetics through their artistic avocations (Root-Bernstein, 1996, 2002, 2003).

These observations suggest that scientists and artists may be being drawn from a single pool of talent, a suggestion we have found the great art historian and critic, Sir Kenneth Clark, made in 1981:

> Art and science . . . are not, as used to be supposed, two contrary activities, but in fact draw on many of the same capabilities of the human mind. . . . The development of science . . . has touched that part of the human spirit from which art springs, and has drained away a great deal of what once contributed to art. . . . We must . . . wait patiently for our faculties to be reunited. (Clark, 1981, pp. 25, 29)

Clark's observation is well worth further investigation, particularly as it has important sociological implications.

ARTS PROCLIVITIES PREDICT SCIENTIFIC SUCCESS

Given the fact that artistic psychological profiles and vocational and aesthetic preferences seem to be correlated with scientific creativity, one might reasonably expect that arts avocations predict scientific success. Many important scientists have conjectured as much. For example, Max Planck, the inventor of quantum physics and a pianist who considered a professional career, wrote in his autobiography that the "pioneering scientist must have an . . . *artistically* creative imagination" (Planck, 1949, p. 109). Similarly, J. H. Van't Hoff (1878/1967), who would become the first Nobel Prize winner in chemistry (1901) suggested that scientific imagination is always mirrored by evidence of nonscientific creativity. Studies of famous living mathematicians and physicists by P. J. Moebius (1900), Henri Fehr (1912), and Jacques Hadamard (1945) suggested he was right.

Subsequent studies by the Stanford University group led by Louis Terman confirmed the polymathy correlation. Terman's student R. K. White produced the first statistical studies of the versatility of geniuses across all disciplines during the 1930s. Analyzing hundreds of historical figures, he found that "the typical genius surpasses the typical college graduate in range of interests and . . . [h]e surpasses him in range of ability" (White, 1931, p. 482). During the 1950s, another Terman student, Catherine Cox, looked at high IQ individuals and found, in Terman's words, that, "there are few persons who achieved great eminence in one field without displaying more than average ability in one or more other fields" (Seagoe, 1975, p. 221). More recent studies by Roberta Milgram and her colleagues at Tel Aviv University following thousands of teenagers from military service through the subsequent 20 or so years of their civilian careers have validated Terman's conclusion. Milgram reports that school grades, IQ, standardized test scores, and psychological profiles do not predict career success reliably. The only reliable predictor of career success in any field is participation of an individual in an intellectually demanding avocation, such as one of the arts, poetry, music, chess, electronics, and so forth, over a long period of time (Milgram, Hong, Shavit, & Peled, 1997). Polymathy of any sort is highly correlated with vocational success.

We have found similar correlations among the forty scientists of the Eiduson study. Eiduson's group eventually included four Nobel laureates and eleven members of the National Academy of Sciences (United States), at one extreme, and several men who never achieved tenure or spent their careers in industry, at the other (Root-Bernstein, Bernstein, & Garnier, 1993). In 1988, Maurine Bernstein (who had taken over the study when Dr. Eiduson died), Robert Root-Bernstein, and Helen Garnier sent out a new questionnaire to the scientists and reviewed Dr. Eiduson's earlier interviews of her subjects. By analyzing publications, citations rates, and multiple interviews, they found that although none of the psychological parameters that Eiduson had investigated correlated with scientific success, statistically significant correlations existed between the number and type of hobbies that a scientist practiced as an adult and his success as a scientist (Table 8.3). In particular, scientists who made or collected art, who practiced photography, or who were active as musicians were much more likely than their colleagues to produce one or more papers cited 100 or more times within 15 years or papers cited 10 or more times in a single year (we called these groupings *citation clusters*). All of the Nobel laureates in the study were in the top citation cluster as were most of the members of the U.S. National Academy of Sciences. The more artistic hobbies a scientist engaged in as an adult, the greater their probability of achieving eminence within science (Root-Bernstein, Bernstein, & Garnier, 1995).

Equally interesting was the finding that the cognitive styles of the scientists were correlated to their avocations. Those who engaged in visual arts or music tended to use various modes of thinking, especially visual and kines-

TABLE 8.3
Hobbies × Citation Cluster for Scientists of the Eiduson Study

	A	B
Painting	.42***	7.64**
Collecting art	.42***	7.64**
Drawing	.29*	5.74*
Sculpting	.12	2.07
Sum of all arts	.38**	—
Poetry	.31**	3.16
Photography	.30**	1.89
Crafts	.31**	2.83
Singing	.25*	4.76
Collect records	.23	2.89
Play instrument	.19	2.07
Nonarts hobbies	−.22	2.95
Sum of all hobbies	.42**	—

Note. A = Pearson product-moment pairwise correlation coefficients. B = Chi-square statistics. Source: Root-Bernstein, et al. (1995).
$^{*}p < .10$; $^{**}p < .05$; $^{***}p < .01$.

thetic, at significantly higher rates than those who had primarily word-related hobbies. Writers tended to think in verbal patterns. Sculptors tended to be nonvisual and kinesthetic thinkers. Those who engaged in electronics-related hobbies used a wide range of mental tools (Root-Bernstein et al., 1995).

In addition, the study found that different modes of problem solving also correlated with scientific success. Scientists who reported solving problems using primarily visual forms of thinking tended to have higher impact and publication cluster rankings than did scientists who used primarily verbal and symbolic forms of thinking. The wider the range of thinking modes a scientist used, the more likely they were to be in the most successful group (Root-Bernstein et al., 1995).

These results raise various interesting possibilities. Do avocations build cognitive strengths or merely mirror them? Do hobbies represent artistic outlets for the scientists' existing mental strengths or do hobbies develop the cognitive bases on which creative science grows? These data obviously do not answer these important questions, but they do make them significant. Likely, future research will reveal that, as with all human traits, innate talents are strengthened by the practice of artistic avocations benefiting vocational skills, and vice versa.

As surprising as the finding that artistic avocations correlate with scientific success may be, it appears to be quite general. We are currently at work on a follow-up investigation of all Nobel Prize winners that is validating the results from the Eiduson study. So far, we have only completed studying the 134 chemists who have won Nobel prizes between 1901 and 2000. We were fortunate to find a control group with which to compare these ex-

TABLE 8.4
Frequency of Arts Avocations in Chemistry Nobel Prize Winners Compared With Sigma Xi Members

Avocation	% Respond @	% Members ~	% Nobelists>
Photography	14.5	1.4	12.8
Music	12.5	1.2	24.6 **
Art +	1.8	0.2	11.9 **
Woodworking ^	1.5	0.1	4.4 **
Writing #	1.2	0.1	9.0 **
Poetry #	0.3	0.03	5.2 ***
Metalworking ^	0.3	0.03	1.5 **
Handicrafts ^	0.3	0.03	ni
Drawing +	0.3	0.03	3.7 ***
Theater or acting<	0.2	0.02	3.7 ***
Etching or printing*	0.2	0.02	1.5 **
Architecture	0.2	0.02	0.7 **
Stagecraft ^	0.1	0.01	0.7 **
Pottery ^	0.1	0.01	0
Weaving ^	0.1	0.01	0
Rugs^	0.1	0.01	0
Sculpture+	0.1	0.01	0.7***
Dancing <	0	0	1.4 +++
Performing (cum <)	0.2	0.02	5.2 ***
Arts (cum +)	2.3	0.2	17.2 ***
Crafts (cum ^)	2.4	0.2	10.4 **
Writing (cum #)	1.5	0.1	12.7 **

Note. Chi-squared analysis using respondents. ** $p < .01$;*** $p < .001$; +++ probability cannot be calculated. Cum = cumulative. ni = no information available. @ c. 4,000 respondents. ~ c. 42,500 members. > 134 chemistry Nobel Prize winners, 1901–2000. Sources include Farber (1961); James (1993); Nobel (2002); and Ward & Ellery (1936).

traordinary scientists in the form of a survey of avocations sent out in 1936 to the members of Sigma Xi, the National Research Society (Ward & Ellery, 1936). Of the approximately 42,500 members of Sigma Xi at that time, just over 4,000 responded to the survey indicating one or more avocations ranging from the arts to gardening and athletics, to stamp, coin, and fossil collecting, to reading. Using the Sigma Xi data as a baseline for calculating distribution and frequency of various hobbies, the same data were collected from biographical and autobiographical sources for the Nobel laureates. For almost all art-related avocations other than photography, Nobel laureates have statistically significantly greater participation in arts avocations as adults than do their peers (Table 8.4). Particularly noteworthy is the fact that Nobel Prize winners practice poetry and other forms of creative writing and the visual arts at rates many times those of average scientists. Although none of the thousands of Sigma Xi members reported dance as an avocation or recreation, two of the Nobel laureates did. Preliminary analysis of the results for Nobel laureates in medicine and in physics show the same strong trends. We therefore feel confident in saying that the most creative scientists not only have the psychological profiles of artists, but more often than not, *are* artists.

SCIENTISTS AND ARTISTS USE COMMON TOOLS FOR THINKING

What benefit can there be for the scientist to be an artist or the artist a scientist? One possibility is that these apparently disparate professions share common ways of creative problem raising and problem solving. Our fourth correlation, therefore, concerns the common cognitive processes shared by artists and scientists. Many individuals, including Arthur Koestler (1964), Loren Eisely (1978), and Jacob Bronowski (1967) have already noted that the creative process as practiced by artists and scientists is virtually identical. One might expect to find, then, that particular cognitive modes used by scientists and artists will also be the same. We spent more than a decade reading hundreds of autobiographical, biographical, interview, and archival sources to determine what creative people in many disciplines say about how they actually think when solving disciplinary problems. Our book-length study, which appeared in 1999 as *Sparks of Genius*, proposed that individuals across the arts and sciences used a similar vocabulary to describe 13 intuitive, imaginative processes. These "tools for thinking" include observing, imaging, abstracting, pattern recognizing, pattern forming, analogizing, empathizing, body thinking, dimensional thinking, modeling, playing, transforming, and synthesizing—all categories that emerged clearly from the sources themselves. Whereas some of these mental tools are well known to psychologists (e.g., observing, imaging, and pattern recognizing), others are in need of much more study (e.g., analogizing, empathizing, and modeling).

Space does not permit a full description of all 13 tools here, but several examples will suffice to demonstrate how artists and scientists similarly define and use them. *Observing*, an essential skill, means paying attention to what is seen, but also what is heard, touched, smelled, tasted, and felt within the body (Berg, 1983). It involves actively seeing rather than passively looking, listening rather than hearing, thoughtfully being in motion rather than merely moving. Georgia O'Keeffe clarified the distinction when she recounted how a teacher "started me looking at things, looking very carefully at details. . . . Still—in a way—nobody sees a flower—really—it is so small—we haven't the time—and to see takes time, like to have a friend takes time" (Root-Bernstein & Root-Bernstein, 1999, p. 32). Nobel Prize–winning ethologist Konrad Lorenz said virtually the same thing: observing takes the "patience of a yogi. . . . To really understand animals and their behavior you must have . . . the patience to look at them long enough to see something" (Root-Bernstein & Root-Bernstein, 1999, p. 36).

Imaging is another mental tool shared by artists and scientists. It is the ability to recall or imagine, in the absence of external stimulation, the sensations and feelings we have observed. We can image visually and also aurally, as well as with smells, tastes, and tactile and muscular feelings (Barlow, Blakemore, & Weston-Smith, 1990; Ferguson, 1992; Roe, 1951). Sir James Black, pharmacologist and Nobel Prize winner, says that the focus of his thinking "is an imaginative sense, entirely open-ended and entirely pictorial. That is a vital part of my life. I daydream like mad . . . you can have all these 'chemical' structures in your head, turning and tumbling and moving" (Root-Bernstein & Root-Bernstein, 1999, p. 53). Composer Henry Cowell said similarly that,

> The most perfect [musical] instrument in the world is the composer's mind. Every conceivable tone-quality and beauty of nuance, every harmony and disharmony, of any number of simultaneous melodies can be heard at will by the trained composer; he can hear not only the sound of any instrument or combination of instruments, but also an almost infinite number of sounds which cannot yet be produced on any instrument. (Root-Bernstein & Root-Bernstein, 1999, p. 59)

Scientists and artists share an ability to create imaginary worlds within their minds.

Observing and imaging produce data that are too complicated to understand in unmodified form. *Abstracting*, whether in science or art, means focusing on a single property of a thing or process in order to simplify it and grasp its essence. Physicist Werner Heisenberg, for example, defined abstracting as "the possibility of considering an object or group of objects under one viewpoint while disregarding all other properties of the object. The essence of abstraction consists in singling out one feature, which, in contrast to other properties, is considered to be particularly important" (Root-Bernstein & Root-Bernstein, 1999, pp. 72–73). This process of eliminating unnecessary information while retaining the integrity of an idea or thing is a "step toward greater generality." Picasso agreed:

> To arrive at abstraction it is always necessary to begin with a concrete reality. . . . you must always start with something. Afterward you can remove all traces of reality. There's no danger then, anyway, because the idea of the object will have left an indelible mark. It is what started the artist off, excited his ideas, and stirred his emotions. (Root-Bernstein & Root-Bernstein, 1999, pp. 71–72)

Once an artist or scientist has found a powerful abstraction, he or she naturally wants to know how generally it can be applied. This process involves *pattern recognizing*, the ability to organize the random events we see, hear, or feel by grouping them. Virginia Woolf, for one, consciously explored pattern recognition in her work. As she developed scenes and characters she felt that she

> put the severed parts together . . . in writing I seem to be discovering what belongs to what. . . . From this I reach what I might call a philosophy; at any rate it is a constant idea of mine; that behind the cotton wool [of daily events lived unconsciously] is a hidden pattern. (Root-Bernstein & Root-Bernstein, 1999, p. 128)

Her purpose in writing was to make that pattern manifest. Many scientists similarly view their purpose as finding the patterns within apparently unrelated data. Nobel laureate Christiane Nusslein-Volhard not only designs her own complex puzzles as an avocation, but likens her embryological work to assembling "pieces of a jigsaw puzzle": "The most important thing is not any one particular piece, but finding enough pieces and enough connections between them to recognize the whole picture"—and to recognize the pattern of the whole picture *before* you have all the pieces (Root-Bernstein & Root-Bernstein, 1999, pp. 104–105, 111).

For many creative people, abstractions and patterns are literally felt within the body rather than seen or heard. Such *body thinking* relies on emotions and proprioceptive sensations of body movement, body tension, and body balance. Sculptor Auguste Rodin wrote that his "Thinker," meant to represent creative individuals of every kind, thought "not only with his brain, with his knitted brow, his distended nostrils, and compressed lips, but with every muscle of his arms, back and legs, with his clenched fist and gripping toes" (Root-Bernstein & Root-Bernstein, 1999, pp. 168–169). Thinking, Rodin tells us, integrally involves how we feel. MIT professor Cyril Stanley Smith, who was considered by many people to be the greatest metallurgist of the past century, certainly found it so:

> In the long gone days when I was developing alloys . . . I certainly came to have a very strong feeling of natural understanding, a feeling of how I would behave if I were a certain alloy, a sense of hardness and softness and conductivity and fusibility and deformability and brittleness—all in a curiously internal and quite literally sensual way even before I had touched the metal. (Root-Bernstein & Root-Bernstein, 1999, p. 171)

Some scientists and artists go even further, not only feeling bodily a thing or idea, but *empathizing* with it, feeling as it would feel. Like an actor, novelist, or playwright, Nobel Prize–winning chemist Peter Debye confessed to solving his problems by thinking about what the characters in his scenario felt—because these were molecules he asked himself, "what does the carbon atom want to do?" Jonas Salk said that he solved the polio vaccine problem by "imagining how the virus would behave" (Root-Bernstein, 1989, pp. 96–97). Philosopher Karl Popper even argued that

> the most helpful suggestion that can be made . . . as to how one may get new ideas in general [is] . . . 'sympathetic intuition' or 'empathy.'. . . You should enter into your problem situation in such a way that you almost become part of it. (Root-Bernstein & Root-Bernstein, 1999, p. 187)

The result of using these mental tools is what chemist–philosopher Michael Polanyi has called "personal knowledge"—an intuitive, sensual, emotional, organic understanding of how things behave or what they mean (Polanyi, 1958). Polanyi's emphasis on "personal knowledge" is particularly noteworthy, because so many philosophers and cognitive scientists reject the possibility that thinking can occur in the absence of verbal or logical formulations. Yet a very large number of the people we have studied describe knowing something intuitively without initially being able to express their understanding.

The rub of intuitive understanding, of course, is that such knowledge is necessarily private. Consequently, many artists and scientists recognize as a key step in their creative process the difficult one of *transforming* imagistic, corporal, empathic ideas into the public language of words, numbers, images, sounds, or movement. They *translate* subjective observations, images, patterns, and body feelings into cogent, disciplinary products that can be reproduced and described objectively. Poet Gary Snyder says that it is a three-step process for him: "The first step is the rhythmic measure, the second step is a set of preverbal visual images which move to the rhythmic measure, and the third step is embodying it in words" (Root-Bernstein & Root-Bernstein, 1999, pp. 8–9). Einstein, who confessed to solving his physics problems in images and muscular feelings, wrote similarly that "[c]onventional words or other signs [presumably mathematical] have to be sought for laboriously only in a secondary stage, when the associative play [of images and feelings] . . . is sufficiently established and can be reproduced at will" (Root-Bernstein & Root-Bernstein, 1999, p. 5). A scientist does not think in mathematical formula, Einstein observed; nor does a poet imagine in words—a point to which we return below in our conclusion. Suffice it to say here that the admonition to "think before we speak" is more insightful than first appears.

Once it is recognized that creative thinking takes place in intuitive, imagistic and private forms before symbolic communication to others, the value of polymathy to the inventive individual begins to clarify. The individual's choice of public discourse determines the domain to which his or her ideas contribute, rather than the way in which the ideas are initially conceived. Polymaths express their personal insights in several domains in order to maximize the process of communication. Moreover, each expression captures different elements of a single insight. In the end, the polymathic, creative individual not only feels that she knows, but knows what she feels in several communicable ways, thereby combining subjective and objective forms of understanding synthetically. We call this *synthetic* form of understanding *synosia* from the Greek roots of the words *synaesthesia* (a combining of the senses) and *gnosis* (knowledge). We believe, along with philosopher John Dewey and historian of science Howard Gruber, that the ability to form integrated networks of enterprise among many avocations and many ways of understanding things is what forms the basis of creative thinking (Dewey, 1934; Gruber, 1988).

SCIENCE FOSTERS ART AND ART FOSTERS SCIENCE

If scientists and artists really think the same way, then it should follow that they can also benefit from insights obtained in the complementary discipline. Art, in short, should foster better science, for, as historian of technology David Pye has written, "One who is capable of invention as an artist is commonly capable also of useful invention" in general (Ferguson, 1992, pp. 23–26). And so we come to our fifth creative correlation between the arts and sciences, which is that artists and scientists often recognize and use arts–sciences interactions in their work.

Roughly one fifth of Nobel laureates in literature have found rich harvest in the study of natural history generally and Darwinian evolution specifically. Sully Prudhomme, whose taste for mathematics and the natural sciences dictated the content of many literary meditations, was known for his "scientific poetry" and philosophical essays on scientific inquiry. Maurice Maeterlinck, best known for his symbolist stories and plays, not only kept bees in his garden but he wrote about them—and termites, ants, and flowers as well—in scientifically accurate essays meant to probe natural analogies to human behavior. At one time or another in their careers, Karl Gjellerup, Frans Eemil Sillanpää, Johannes Jensen, and John Steinbeck all parlayed an intense interest in Darwinian evolution and other scientific theories into thematic materials driving their novels, poetry, plays, and essays (Liukkonen, 1999; Nobel, 2002; Pribic, 1990). Jensen explicitly recognized the connection between his scientific avocation and his literary recreations of large sweeps of human history. He wrote in his Nobel autobiography: "The grounding in natural sciences which I obtained in the course of my medical studies, including preliminary examinations in botany, zoology, physics, and chemistry was to become decisive in determining the trend of my literary work" (Nobel, 2002). In the six-volume epic cycle that earned him the Nobel, this trend involved a personal interpretation of evolutionary theory and its moral implications as it applied to the cultural past and present. John Steinbeck similarly meshed scientific and literary interests. In his collaboration with the ecologist Ed Ricketts on *The Sea of Cortez* (1941/1971), Steinbeck not only returned to the marine biology he had studied in college, he determined that the shaping of science writing was as creative an act as the shaping of his fiction. Moreover, he used Ricketts' conceptual insights into the interrelated ecology of all life in *To A God Unknown* and other novels (Liukkonen, 1999; Pribic, 1990).

Science has also had a tremendous impact on the arts through studies of perception, color theory, perspective, and other novel geometries and the development of new techniques and instruments. A vast literature exists on this topic, so we will not describe it here (e.g., Kemp, 1990; Strosberg, 1999; Vitz & Glimcher, 1984; Waddington, 1969). Suffice it to say, art is permeated with scientific and technological know-how transferred there both by scientific artists and artistic scientists. A phenomenon that is less well known is that science is also permeated with art. Historian Brooke Hindle has spent a lifetime documenting art-to-science creativity for a wide range of artists-turned-inventors. His most famous case study involves two of America's greatest inventors, Samuel Morse and Robert Fulton, both of whom established themselves among the very best American painters before turning, in middle age, to careers as inventors (Hindle, 1981). More to the point, for both men, artistic training made possible and informed the nature of their inventions. Just to give one example, Morse's first working model of a telegraph was made out of a canvas stretcher adapted from his painting days.

Hindle suggests in this and many other cases that technical and manipulative skills developed in art were essential to industrial invention. In addition, a great many eminent anatomists of the 19th and early 20th centuries—Francis Seymour Hayden and Nobel laureates Santiago Ramon y Cajal and Emilio Golgi among them—formally trained themselves in visual arts because, as Hayden put it, "How much sooner would the eye [trained to draw] . . . learn to gauge the aberrations which make up the facies of the disease; how much better the hand, trained to portray them accurately, be able to direct with precision and safety the course of the knife!" (Zigrosser, 1976, p. 148; see also Berg, 1983). In other sciences, as well, artists have used their highly honed observational skills to discover what others overlooked. The protective coloration and patterning of animals that we call camouflage was discovered not by a biologist but by a late 19th century portraitist and painter of angels, Abbott Thayer, whose hobby was evolutionary theory (Root-Bernstein, 2000).

Artists also invent new structures that scientists then discover in nature. Virologists attempting to understand the structure of the protein shells that surround spherical viruses such as polio during the 1950s were directed by knowledge of architect–writer Buckminster Fuller's geodesic domes. Fuller's architecture also became the model for 60-unit carbon spheres aptly named buckminsterfullerenes, which are the most stable chemicals in the universe. Their inventor, Nobel laureate Hans Kroto, is himself an amateur artist who was aware of Fuller's concepts (Root-Bernstein, 2003). Cambridge physicist and artist Roger Penrose has also invented a new fundamental structure by playing around with variations of Escher-style tilings called aperiodic, or nonrepeating, tilings. He soon turned his recreation into a professional asset by working out the mathematical properties of such aperiodic tilings and giving the field its first complete theory. Martin Gardner's mathematical recreations column in *Scientific American* brought Penrose's avocation to the attention of a broad array of scientists, some of whom recognized that aperiodic tilings explain anomalous crystal structures in metal alloys called *quasicrystals* (Root-Bernstein, 2000). In this manner, artistic exploration has led to multiple scientific insights. Indeed, we would argue, artistic and scientific thinking are not two different kinds of cognitive activity, but two aspects of the same creative impulse.

CONCLUSIONS: CREATIVITY AS CONCEPTUAL COMPLEMENTARITY

To summarize, we have found that artists and scientists, and also artistic and scientific thinking, are more similar than they are different. Many scientists pursue artistic avocations throughout their lives. Many artists reciprocate. Psychologically, scientists and artists appear to be very similar to each other in cognitive and personality factors and quite different from people who choose business- and humanities-related vocations, suggesting that scientists and artists may be drawn from a single, discrete pool of talent. Scientists and artists use a common set of intuitive and personal "thinking tools" for recognizing and solving their problems; practicing these mental tools in one field may foster their use in other fields. The pursuit of artistic activities by scientists correlates significantly with success as a scientist. We presume, but currently lack appropriate control groups, that the same correlation exists between polymathy and success in the arts. We hypothesize further that polymathy correlates with success in any discipline, as Roberta Milgram's data suggest. Certainly, many scientists, artists, and writers are explicitly aware that they have benefited from integrating disparate disciplinary interests. Thus, arts foster scientific creativity and conversely science fosters artistic creativity.

Should we recommend, then, that all students, regardless of vocational goals or personal preferences, take classes in painting, printing, sculpting, music composition and performance, dance, theater, creative writing, mathematics, and the sciences, as a way of fostering creative potential? If only it were so simple. No; what our research shows is something more subtle and difficult to achieve, and that is that creative people *integrate* apparently disparate skills, talents, and activities into a synergistic whole. A *functional interaction* must exist between intellectual and aesthetic activities to make avocations of value to vocational goals. Dewey has called this polymathic interrelatedness "integrated activity sets" (Dewey, 1934), Gruber dubbed it "networks of enterprise" (Gruber, 1988), and we have used the term "correlative talents" (Root-Bernstein, 1989). All three terms refer to an ability to recognize *useful* points of contact and *analogous skills* among an apparently diverse set of interests. Merely requiring a "distribution requirement" of "creative" activities will not, therefore, achieve synthetic talent integration.

The phenomenon of correlative talents does, however, have immediate implications for cognitive studies. Howard Gardner (1999) and Mihalyi Csikszentmihalyi (1996) have made it fashionable to argue that creativity occurs only within recognized domains of cognitive activity such as the visual–spatial or musical or kinesthetic or logico–mathematical. Gardner has gone so far as to doubt the possibility of "horizontal faculties" that would allow transdisciplinary or transdomain creativity (Gardner, 1999, p. 104).

Yet the pervasiveness of polymathy among innovators in both the sciences and arts argues strongly for the existence of horizontal faculties of some sort.

We suggest that one of the primary reasons that Gardner and Csikszentmihalyi ignore these horizontal faculties is that they have focused their research on the unique types of *products* that characterize disciplines or domains rather than on common creative *processes* that transcend them. This focus on product is built into their work from the outset. Gardner's "frames of mind," for example, are defined by the existence of unique, domain-specific languages and artifacts by which they can be identified (Gardner, 1999). His mistake, from our point of view, has been to confuse the formal mode of communication chosen by individual creators with the mode in which they do their creative thinking. As we have pointed out above and documented elsewhere (Root-Bernstein, 2001, 2002, 2003; Root-Bernstein & Root-Bernstein, 1999), creative people use personal and intuitive tools for thinking to achieve their insights, resorting *only in an explicitly secondary step* to translating their personal knowledge into a formal language in order to communicate with other people. Although we have no doubt that Gardner and Csikszentmihalyi are correct to contend that most (but not all) people have a *preferred mode of communication*, we strongly object to their assumption that people *think* in the same terms that they use to communicate. Our research suggests that thinking and communicating require very different skills. Creative artifacts and expressive products are transformations of thought and therefore unreliable guides to the processes by which those thoughts are generated. Languages are certainly based in cognition but cognition is not based in language (Barlow, Blakemore, & Weston-Smith, 1990; Root-Bernstein & Root-Bernstein, 1999).

One consequence of our view that cognition and communication are separate skills is that we find the concepts of domains, disciplines, and even vocations and avocations problematic. Hutchinson, whom we quoted above, hit the nail on the head when he said that for the most creative people, disciplines disappear. Creative people tend to have multiple forms of training, several kinds of jobs, and many ways of expressing themselves that ignore accepted categories and expectations (Root-Bernstein & Root-Bernstein, 1999, chaps. 15 & 16). How, for example, shall we describe Sophya Kovalevskaya, who attained international recognition as both a poet–playwright and also as one of the greatest mathematicians of the 20th century? Each activity fed the other in her mind:

> You are surprised at my working simultaneously in literature and in mathematics. Many people who have never had occasion to learn what mathematics is confuse it with arithmetic and consider it a dry and arid science. In actual fact, it is the science which demands the utmost imagination. . . . The poet must see what others do not see, must see more deeply than other people. And the mathematician must do the same. (Kovalevskaya, 1978, pp. 102–103)

Getting a grasp on polymaths is difficult because the very categories embedded in our language militate against a satisfactory description of transdisciplinary activity. Is Desmond Morris a scientist because he spent much of his life as a professor of zoology at Oxford University; or is he a writer because he has written dozens of best-selling books; or is he a filmmaker because he has created art films and dozens of documentaries on animal and human behavior for the BBC, The Learning Channel, and other stations; or is he an artist because he has spent more time creating and showing his Surrealist paintings than doing anything else? Morris, whose passport labels him as a zoologist, identifies himself as none of these things. "I never thought of myself as a zoologist who painted or as a painter who was interested in zoology. They are both equally important to me because they both involve visual exploration" (Morris, 1987, p. 9). He goes on to say that

> If my paintings do nothing else, they will serve to demonstrate that such titles are misleading. In reality, people today are not scientists or artists . . . they are explorers or non-explorers, and the context of their explorations is of secondary importance. Painting is no longer merely a craft, it is a form of personal research. . . . So, in the end, I do not think of myself as being part scientist and part artist, but simply as being an explorer, part objective and part subjective. (Morris, 1971, p. 25)

Elsewhere Morris calls for the abolition of categorical thinking in a manner that strikes us as a fitting summary of our own argument as well: "Perhaps the time will come when we will give up the folly of separating subadults into the imaginative and the analytical—artists and scientists—and encourage them to be both at once" (Remy, 1991, p. 18).

So many innovative people are anomalously "both at once" that those who study creativity must pay attention. We conclude by suggesting that it is the very fact that polymaths cannot be pigeonholed into one discipline or domain that accounts for their extraordinary creativity. Innovations, by definition, are effective surprises that bring together problems, concepts, techniques, and materials that were previously unrelated (Root-Bernstein, 1989). By exploring many different ways of being "small c" creative, polymaths master an unusually wide range of imaginative and technical skills that reveal unexpected analogies between weakly related fields. Their innovations create formal bridges where none existed before, opening the way for "big C" creativity that redefines disciplinary boundaries and cognitive domains.

We further suggest that the fact that creative polymaths straddle domains explains why "genius" is so often associated with a struggle for recognition, whereas "normal" activities (in the Kuhnian sense) are often highly rewarded, but rarely remembered by posterity. Creativity is revealed through the intellectual and social redefining of boundaries, of which the creative product is simply a physical manifestation. The reason that the mimic or forger is not considered creative, though his or her product may be indistinguishable from the original, is because creativity lies not in the product, but in the *process of bridging and linking* domains. For Creative people, C. P. Snow's "two cultures" have never existed (Root-Bernstein et al., 1995; Root-Bernstein & Root-Bernstein, 1999). If there *is* a divide in creative culture that withstands scrutiny, it is between those who alter disciplines and their boundaries and those who do not. The first are likely to cultivate highly correlative, polymathic talents. The second are more likely to be highly specialized individuals and less likely to combine relevant avocations with vocation. Only when the imaginative processes that enable polymaths to link knowledge in new and extraordinary ways and the correlative talents that allow them to transcend the public discourse of disciplines are more fully understood will creative thinking yield up its secrets to cognitive science.

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