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The Art of Innovation: Polymaths and Universality of the Creative Process

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Abstract: Many people view arts and sciences as being different because sciences yield objective answers to problems whereas arts produce subjective experiences I argue that art and science are on a continuum in which artists work with *possible* worlds whereas scientists are constrained to working in *this* world. But sometimes perceiving this world differently is the key to making discoveries. Thus, arts and sciences are on a continuum in which artistic thinking produces possibilities that scientists can evaluate for efficacy here and now. Not surprisingly, then, many of the most innovative scientists have had avocations in the arts, and some of the most innovative artists have had avocations in the sciences. These polymaths have often written or spoken about how their arts involvments have benefitted their scientific creativity and may provide a model for fostering a more innovative education.

Keywords: Innovation; Polymathy; Artscience; Creative process; Avocations; Hobbies.

Introduction: The Universality of Creative Thinking

Innovation in science and engineering is often portrayed as if it were distinct from that in the fine arts, perhaps because most definitions of innovation center on the idea of *effective problem-solving*. Science and engineering are supposed to be objective, intellectual, analytical, and reproducible so that it is clear when an effective solution has been achieved to a problem. The arts, literature, and music, by contrast, are portrayed as being subjective, sensual, empathic, and unique, so that it is often unclear whether a specific problem is being addressed, let alone whether a solution is achieved. It therefore comes as a considerable surprise to find that many scientists and engineers employ the arts as scientific tools, and that various artistic insights have actually preceded and made possible subsequent scientific discoveries and their practical applications. These trans-disciplinary interactions must cause us to reconsider how we think about innovation.

There are four important ways in which innovative ideas flow between the professions. One is through problem generation (see Root-Bernstein, 'Problem Generation and Innovation' in this volume). The arts often invent or discover phenomena and observations unknown to the sciences. A sceond role that the arts play is to provide scientists and engineers with non-traditional physical and mental tools, analogies and models that can be used to solve problems. More on this below. Third, the arts often provide scientists with the tools necessary to communicate their results—with the considered use of words, images, and modeling techniques necessary to reify ideas as theories and explanations. The aesthetic portrayal of results in the sciences is just as important as in the arts and relies upon the same tools. And finally, the arts contribute to scientific innovation through *fantasy*, that is to say, through *the generation of possible worlds* that scientists can test according to the constraints of what is known about the real world. This fourth type of sciences–arts interactions is the one most often overlooked and of the widest application to understanding innovative thinking in general.

All real-world innovation is a process that involves the elaboration through fantasy (sometimes called imagination) of many possible solutions to any given problem, and the use of the widest range of mental and physical tools to constrain and evaluate which of these possibilities is most adequate to any given need. In this sense, all innovation is a process of survival of the fittest in which multiple variations of ideas are selected by social, economic, cultural and other factors

(Nickles, this volume; Root-Bernstein, 1989). What the arts provide the sciences is the ability to imagine possibilities—possible problems, possible tools, possible solutions—through synthetic and sensual forms of thinking to which analytical and logical forms of thinking can later be applied as part of the selection process. In short, I maintain that effective solutions to problems (i.e. innovation or creativity itself) can only be achieved if a *range* of possible solutions have been elaborated that can be examined for their relative effectiveness. Arts foster sciences and technology by elaborating possible worlds that can be evaluated for the insights they provide to the real world.

Note at the outset that I am not claiming that art is science or science, art. A painting is not usually a scientific diagram; each has distinct purposes and goals. A short story is not usually a scientific paper and no intelligent person could confuse them under most circumstances. A sculpture is not usually equivalent to a molecular model, nor do they have the same functions. But sometimes they do.

Sometimes what an artist imagines might be possible turns out to be what actually is. Unexpectedly, a painting can sometimes be a way to generate scientific ideas; fiction can explore and even propose new scientific theories; and sculptures can be scientific or mathematical models. The purpose of this essay is to argue that there exist fundamental connections between sciences and arts that provide non-trivial windows onto the gardens of the mind where innovative thinking is cultivated.

The key to understanding my approach to innovative thinking in the arts and sciences is to distinguish clearly between disciplinary products and trans-disciplinary processes. I believe, along with Koestler (1964), Bronowski (1967), and many others including Weisberg in this volume, that no distinction exists between the arts and sciences at the level of the creative process itself (Root-Bernstein, 1984, 1989). The ways in which artists and scientists discover and invent problems, experiment with ways to come to grips with them, and generate and test possible solutions is universal. In fact, most of the greatest innovators in every discipline have been polymaths—Renaissance people like Leonardo da Vinci— who demonstrated their creative abilities in several fields of endeavor. Thus, I propose that creative people are generally creative, and their general creative ability comes from mastering a common set of thinking tools (see Root-Bernstein & Root-Bernstein, 'Intuitive Tools for Innovative Thinking' in this volume) and a creative process that is similar across all disciplines. This point can be made particularly effectively through examples of artists who have made scientific discoveries, scientists who have made artistic contributions, and those who bridge both sets of disciplines without claiming allegiance to one or another. As rare as such examples may be (I will argue that they are unexpectedly common), the very fact that polymaths make trans-disciplinary discoveries should warn us against making too-easy distinctions between disciplines or cognitive domains. On the contrary, I will argue that those people who incorporate (in a quite literally visceral way) modes of thinking belonging to many cognitive domains are those most likely to become innovators.

Polymathy as a Predictor of Success

Santiago Ramon y Cajal, one of the first Nobel Prize Winners in Physiology or Medicine, is remembered today for his ground-breaking work on neuroanatomy. He was also a talented artist and photographer who attributed much of his scientific success to these avocations. Not only did he proclaim that, "it is not without reason that all great observers are skillful in sketching", but he also avowed that only through neuranatomical studies were his strong "aesthetic instincts" satisfied by the "incomparable artistic emotions" he experienced. Ramon y Cajal recognized that his polymathic tendencies were unusual, but asserted in his autobiography that the most successful scientists were, like him, "endowed with an abundance of restless imagination spend(ing) their energy in the pursuit of literature, art, philosophy, and all the recreations of mind and body. To him who observes them from afar, it appears as though they are scattering and dissipating their energies, while in reality they are channeling and strengthening them" (Ramon y Cajal, 1951, p. 171). To be creative, Ramon y Cajal said, one had to have wide experience with the process of creating.

A surprising number of his contemporaries agreed. Charles Richet, another Nobel laureate and a celebrated playwright, wrote: "Generally those who later become illustrious (in science) have shown from the first, by their aptitude for history, science, literature, languages, that they were superior to their contemporaries" (Richet, 1927, p. 128). Similarly, J. H. van't Hoff, the first Nobel laureate in Chemistry (1901) and himself a musician and poet, proposed that the development of the scientific imagination requires the development of artistic, musical, and poetic talents. In a famous address on 'Imagination in Science' (van't Hoff, 1878), he listed dozens of examples of eminent scientists who were multiply talented, including such notables as Kepler (a musician), Galileo (an artist), Davy (a poet), and Pasteur (another artist). He concluded his address by arguing that often the poetic vision outstrips the scientific showing the latter the way to the truth. This is a point to which I shall return below.

Many of van't Hoff's contemporaries saw the same connections between artistic proclivities and scientific success that he did. Van't Hoff's friend and colleague Wilhelm Ostwald produced a large body of work on scientific genius that validated the polymathy hypothesis (Ostwald, 1909). The English polymath, Francis Galton found that polymathy was unusually common among members of the British Royal Society (Galton, 1874). Botanist P. J. Moebius, the grandson of the famous mathematician, and the Frenchman Henri Fehr both noted independently the unusually high incidence of artistic and musical proclivities among two large groups of mathematicians (Fehr, 1912; Moebius, 1900). Jacques Hadamard confirmed these findings several decades later in his classic, *The Psychology of Invention in the Mathamatical Field* (Hadamard, 1945). All of these studies were summarized by the Nobel laureate and pianist Max Planck when he suggested that scientific success depends upon the use of an '*artistic* imagination' (his emphasis; Planck, 1949, p. 14).

When so many successful scientists all say that artistic imagination fosters good science, one must wonder whether it might not be true. In fact, a large body of psychological literature supports the hypothesis that polymathy is correlated with career success. For example, Stanford psychologist Lewis Terman, the father of the Stanford Binet IQ test and one of the foremost investigators of high achievers, wrote in 1941 that: "While the versatility of geniuses has long been stressed by biographers (e.g. of Da Vinci), the less spectacular cases are usually overlooked. People prefer to believe that the genius, as a rule, is no better than the rest of us except in one particular. The facts are very different . . . . 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). His conclusion was based upon decades of study of high achievers followed from their school days well into their careers, much of it published by his collaborator Catherine Cox. He also drew on studies of historical figures carried out by his colleague R. K. White. Analyzing hundreds of historical figures, White had found that "the typical genius surpasses the typical college graduate in range of interests and . . . he surpasses him in range of ability" (White, 1931, p. 489). Similarly, historian of science Paul Cranefield found that there was a direct correlation between the eminence a scientist achieved and his range of activities. The number of avocations practiced by a scientist correlated with the number of different scientific areas in which he worked. The number of different areas in which each scientist worked correlated with the number of significant discoveries they made. And the range and nature of the subjects that a scientist addressed in their research correlated with their cultural and philosophical avocations (Cranefield, 1966).

Subsequent cognitive studies have tended to validate the notion that the versatility of genius provides useful mental skills. For example, studies by Rauscher et al. and Gardiner et al. have suggested that direct relationships may exist between art and musical skills and improved spatial and mathematical reasoning in children (Graziana, Petterson & Shaw, 1999; Gardiner et al., 1996, p. 284; Rauscher, Shaw & Ky, 1997). Similar results exist for adults. An 11-year follow-up of participants in Project TALENT by Humphreys et al. (1993) has shown that in college students neither high grades nor high scores on verbal and mathematics tests are predictive of future participation or success in engineering and physical sciences. High scores on spatial and mechanical comprehension tests were, however, predictive, especially when combined with high mathematics scores. Schaer et al. (1985), Woody Flowers at MIT, and various other investigators (Stewart, 1985) have shown that it is possible to train scientists and engineers through explict visualization and drawing exercises to improve their imaging and modeling skills, thus bringing the arts–sciences connection full circle.

Avocations can be as useful in training the creative mind as can formal classwork. Students who develop artistic skills through natural inclination tend to have much improved success in all careers according to a huge, long-term study of Israeli professions carried out by Milgram et al. (1993). They found that high IQ, standardized test scores, and high school grades were not good predictors of career success either independently or as aggregate measures. The best single predictor of success in any field, including the sciences, was participation as an adolescent in what Milgram calls "challenging leisure-time activities", i.e. avocations that require significant intellectual and time commitments. These include music performance and composition, painting, drawing, photography, chess, electronics, programming as a hobby, and creative writing, among others. These activities appear to be surrogate measures not only of intellectual ability, but energy, self-motivation, task commitment, cognitive breadth, and other attributes that strongly influence success.

Continued participation in the arts as an adult is also highly predictive of success as a scientist. A convenience sample of 40 scientists recruited by Bernice Eiduson in 1955 for a psychological study was analyzed by Root-Bernstein et al. in 1988 (Root-Bernstein, Bernstein & Garnier, 1993). By then, the group included four Nobel laureates, 11 members of the National Academy of Sciences (USA), many typical university professors, as well as several individuals who left academia for industry. Two measures of success were employed: impact (the ratio of citations to publications) and citation cluster (people with one or more papers having more than 100 citations over a 15 year period; people with one or more papers having between 10 and 100 citations in a single year; people with one or more papers having between 10 and 100 citations over 15 years; and people who met none of the previous criteria). The Nobel laureates were all in the top impact group and citation cluster, as were most of the National Academy members. Statistically significant correlations were found between success as measured by impact ratio and participation as an adult in painting, drawing, and sculpting. Significant correlations were found between success as measured by citation cluster and painting, collecting art, writing poetry, photography, crafts, singing, and most strongly with the sum of all hobbies. In short, these correlations validated the anecdotal evidence collected by Ramon y Cajal, Richet, van't Hoff and so many other Nobel laureates (Root-Bernstein et al., 1995).

Root-Bernstein et al. (1995) also found that statistically significant correlations existed between various hobbies and the modes of thinking that the scientists reported using during their scientific work. Artistic scientists tended to be visual and imageless-nonverbal thinkers whereas musicians were predominately visual thinkers. The link found between music training and improved visualization by Graziano et al. (1999), Gardiner et al. (1996) and Rauscher et al. (1997), therefore seems to extend into adulthood. Sculptor-scientists were mainly imageless-nonverbal and kinesthetic thinkers. Writer-scientists, not surprisingly, were mainly verbal thinkers; and those who participated in electronics-related hobbies tended to use the widest range of modes of thinking. How we think about problems therefore seems to be a function of what mental skills we develop through practice. Moreover, modes of thinking were independently correlated with measures of scientific success. Success as measured by impact ratio correlated significantly with visual thinking, use of verbal/auditory patterns, kinesthetic thinking, and other unusual forms of thinking such as use of word images, acoustic images, and talking to oneself. Success as measured by citation clusters, however, correlated most strongly with use of visual images, and visualized symbols and words.

These results do not distinguish between three non-exclusive possibilities. First, the most successful scientists may simply be very bright people who could succeed at anything. Second, innate talents are expressed in both scientific style and avocations. And third, practice using certain modes of thinking leads to skill development that is trans-disciplinary. Interviews with the scientists lead me to favor the latter hypotheses. The most successful scientists all percieved the sciences and arts to be complementary or compatible, as opposed to the less successful, who saw them in conflict. Some of the most successful went on to describe, like Ramon y Cajal, ways in which their avocations stimulated their scientific acumen.

I am not claiming that to become a successful scientist one *must* cultivate the arts, music, or literature. There are many ways of learning how to think visually, kinesthetically, and by analogies, including the practice of science itself. In fact, until recently, both free-hand and mechanical drawing, model building, and writing were integral parts of many science and engineering curricula. But due to larger classes, fewer labs, and monetary restrictions, arts and crafts programs now retain almost exclusive hegemony over such skills. Still, their continued necessity in science and engineering training has been urged in books as varied as Eugene Ferguson's *Engineering and the Mind's Eye* (Ferguson, 1992), Cyril Stanley Smith's *A Search for Structure* (Smith, 1981), Geri Berg's *The Visual Arts and Medical Education* (Berg, 1983), Phillip Ritterbush's *The Art of Organic Forms* (Ritterbush, 1968), and my own *Discovering* (Root-Bernstein, 1989). All of these studies tell us that artistic scientists and engineers have more image-ination, musically talented ones duet (do it) better, and the verbally inclined have the skills to become pundits. Seriously. Being cultured is still a prerequisite to being educated, and education is still a requirement for being successful.

The Uses of Arts by Scientists

The fact is that scientists and inventors not only explore the arts as avocations, but use them in their professional work (Root-Bernstein, 1985, 1987, 1990, 1997, 2001). Astrophysicist and novelist Gregory Benford points out, "Many believe that science fiction (SF) writers get their ideas from science and often this is so. Fewer recall that ideas have also flowed the opposite way" (Benford, 2001, p. 1). The Russian rocket pioneer Konstantin Tsiolkovsky was inspired to begin inventing by the works of Jules Verne; Leo Szilard took out the first patent on nuclear reactors after reading a short story by H. G. Wells about the potential for unlocking the energy stored within the nucleus of atoms; and Benford himself explores in his fiction the ideas that he cannot carry out as a scientist.

The use of fiction to explore novel scientific ideas is hardly rare. Robert L. Forward, an astrophysicist and inventor who is also an award-winning science fiction writer, says of his work: "Those of (my) far-out ideas which can be accomplished using present technology (I) do as research projects. Those that are too far out (I) write about in speculative science articles or develop in (my) short stories and novels" (Forward, 1985, book-jacket). Forward insists that his science and his fiction are on a continuum, his fiction simply consisting of the ideas that are currently beyond his means to implement. That does not mean that these ideas are any less valuable or insightful. As science fiction writer Jeff Hecht notes, "Fictional inventions take real skill and some prove truly prescient" (Hecht, 1999, p. 59). Recognition that important innovations are foreseen by scientific novelists has now become so explicit that the European Space Agency recently announced that they are scouring science fiction for new space propulsion technologies (Anon., 2000, p. 41). Similarly, corporations such as Global Business Network hire scientist-novelists such as computor innovator Vernor Vinge because they provide "an unbelievably fertile perspective from which to look back at and reunderstand the present. It's that ability to conceptualize whole new ways of framing issues .... He has contributed to the turnarounds of at least two well-known technology companies" (Hafner, 2001, D9).

Poetic scientists find similar connections between their poetry and their science. Words are scientific tools just as much as they are artistic ones, and therefore the exercise of words can be as enlightening to a scientist as to a writer. Thus, Nobel-prize-winning chemist Roald Hoffmann says that, "I begin with a vision of unity of creative work in science and in the humanities and arts . . . . I have no problem doing (or trying to do) both science and poetry. Both emerge from my attempt to understand the universe around me, from my own personal affection for communicating, teaching what I've learned, and from my infatuation with language . . . . It seems obvious to me to use words as best I can in teaching myself and my coworkers. Some call that research . . . . The words are important in science" (Hoffmann, 1988, p. 10). Similarly, physician and poet Jack Coulehan maintains that writing poetry makes him a better physician: "Both disciplines require careful observation. Both focus on the concrete—an illness, an event, a feeling—over the abstract. In fact, William Carlos Williams' famous aphorism about poetry, 'No ideas but in things', is also a good prescription for medical practice . . . . Moreover, a physician's ability to empathize with a paitient is a creative act analgous to the poet's act of exploring the subject of a poem . . . . (And), like poetry, medicine achieves much of its powerful effect through the use of symbol and metaphor" (Coulehan, 1993, p. 57). To learn how to manipulate images and feelings through the words of a poem is therefore, according to Hoffmann and Coulehan, to learn how to manipulate the images and feelings that are expressed in scientific symbols as well. **Equally important, learning to manipulate language teaches imagination without great science is not possible**.

Author: Sense?

Ethologist and Surrealist painter Desmond Morris has said that he uses his art for the same reasons that scientific fiction writers and poetic scientists practice theirs. "Being a biologist and a student of evolution, I attempted to evolve my own world of biomorphic shapes, influenced by but not directly related to the flora and fauna of our planet. From canvas to canvas I have tried to let them grow and develop in a natural way, without ever crudely borrowing specific elements from known animals or plants" (Morris, 1987, p. 17). He says that his biomorphic shapes undergo the same evolutionary stages that real organisms do so that his art becomes a mental laboratory for exploring the nature of evolutionary processes in the abstract. He realizes explicitly that his "paintings are very biomorphic, very preoccupied with biological shapes, and that my biological writings are largely concerned with visual patterns of behaviour. I have never resisted that kind of leakage . . ." (Remy, 1991, p. 18). In fact, he has made that leakage the source of fertile studies of the biological origins of art and of the evolution of primitive arts among humans, an interest he shared with another evolutionary pioneer, Mary Leakey, who began her scientific career as an illustrator for other anthropologists (Leakey, 1984, pp. 39–43).

Many evolutionary and ethological studies have been influenced by artistic biologists. Thomas Henry Huxley, Alfred Russel Wallace (Nelson, 2001, p. 1260), and Ernst Haeckel are only a few of the pioneers of evolutionary theory who were also artists. Haeckel, whose prints (Haeckel, 1905) had a significant impact on the artists of his day (Kockerbeck, 1986), was the first to fully realize Darwin's concept of an evolutionary tree as an articulated image. Huxley for his part claimed that accurate scientific observation was impossible without a facility for drawing and argued that art classes should be required for all scientists: "I should make it absolutely necessary for everybody, for a longer or shorter period, to learn to draw . . . . I do not think its value can be exaggerated, because it gives you the means of training the young in attention and accuracy, which are the two things in which all mankind are more deficient than in any other mental quality whatever" (T. H. Huxley, 1900, vol III, pp. 183–184).

Contemporary artistic scientists include ethologist Jonathan Kingdon (Gautier-Hion et al., 1988) and paleontologist-novelist Robert Bakker (Bakker, 1995), both of whom draw their own specimens and create three-dimensional models from their sketches in order **to with their material**. Bert Holldobler, a professor of entomology and an amateur painter, also draws the illustrations for all of his publications. He says that, "It is my urge that I make every paper I write as crystal clear as I can in words and illustrations. A scientific publication should be a piece of art" (personal communication). His success is proven by the fact that he won a Pulitzer Prize for his collaboration with E. O. Wilon on their book, *The Ants*, of which Holldobler says, "It was our first intention to write a scholarly book, but we were also driven to show the beauty of the life of our subjects, both in our writing and in the illustrations of the book" (personal communication). For these men, an illustration is therefore both art and science.

Author: Missing words?

Another example of art having a scientific component and science having an intrinsic artistic element can be found in the subject of moire patterns. Moire patterns are created when figures with periodic patterns are made to overlap so that both patterns are still visible. The word '**moire**' comes from the French word for 'watered' and has classically been used to describe the particular type of silk fabric that has the shimmer of water waves. This shimmer results from folding the silk onto itself at a slight bias and then pressing it under high pressure and heat to imprint the slightly offset pattern of one fold of the fabric onto the other. Similar patterns can be created by overlapping two or more screens or meshes, or by drawing overlapping patterns

Author: 'moire' or 'moiré'?

on paper. Physicist Gerald Oster demonstrated that moire patterns have many interesting mathematical properties, including the potential to perform analogue computations, thereby calculating by visual means (Oster & Nishjima, 1963). Oster not only published widely on the scientific uses of moire patterns, but also exhibited them as art in several well-known galleries (Mueller, 1967, pp. 197–198).

In a similar way, music has played its role in scientific developments. Musical analogies are so commonly used by scientists that historian of science Jamie Kassler has written a book describing their many problem-solving functions (Kassler, 2001). Not only did Johannes Kepler derive many of his astronomical discoveries from attempts to optimize the 'harmony of the spheres' (which he wrote out literally as music!) but physicist-musician Louis de Broglie earned himself a Nobel prize by comparing atoms to tiny stringed instruments and then showing that they would have the same kinds of harmonics and overtones, but with frequencies proportionally smaller. In these cases, the links between music and science are apparent and often describable as mathematics. Sometimes scientists therefore take advantage of the music–mathematics equation to convert quantitative results into music! Many university profeessors and corporations, including Bell Labs, Exxon Research and Engineering Corporation, and Xerox have experimented with transforming complex quantitative data into sound. They have discovered that the ear has powers of pattern recognition that extend far beyond the discriminatory abilities of the eye, and therefore that turning data into music rather than into graphs or charts often aids analysis. Applications of this technique have included exploring the patterns within the human genome, chemical analyses, complex physiological data, and multivariate economic indicators (Peterson, 1985a).

Sometimes scientists use music less analytically and more inspirationally, raising interesting issues about what stimulates creative thinking. Cardiology researcher Richard Bing, for example, is also a composer. He says that, "Writing music enriches me to look at science in a different way. It helps me emotionally to feel more about science. You see, I am a romanticist. I perceive science as an emotional exercise of searching the unknown" (Root-Bernstein, 1987, p. 2). Bing believes, as did Einstein, that "both (music and science) are born of the same source and complement each other through the satisfaction they bestow" (Clark, 1981, p. 106). This may explain why scientists from Darwin to Einstein and inventors such as Charles Martin Hall have all turned to music when faced by an apparently unresolvable problem. Somehow music frees the analytical mind allowing intuition to yield its fruits (Root-Bernstein, 2001).

Even dance has placed its footprints in scientific innovation. Berkely physicist Marvin Cohen has collaborated with choreographer David Wood and his dancers to explore forms of dynamic symmetry that inform the theory of super-conductivity. Cohen describes the dance not only as a novel way to communicate his otherwise inaccessible mathematical theories, but also as a form of 'research'. He hopes that the dancers will invent forms of dynamic interactions that physicists have yet to have considered as possible models for electron interactions (NOVA, 1988). Dance notations are playing a similar role in elucidating the visualization problems that plague neurology and other areas of medicine. Describing and accurately communicating the nature of the motor impairments that characterize particular neurological lesions and various genetic diseases has always been extremely difficult. How does one explain to someone that multiple sclerosis is typified by this type of gait, but amyotrophic lateral sclerosis presents a different set of motor impairments that look quite different? That problem was first solved about 20 years ago by neurologists Ilan Golani and Philip Teitelbaum, when they applied Eshkol–Wachman movement notation, a well-known tool for recording dance movements, to the description of laboratory animal and human movement diseases (Golani & Teitelbaum, 1979). Since that time, Labanotation and Benesh Movement Notation have also been applied to the recording and analysis of physical actions. Someday, they may inform our design and control of robots as well.

The arts, in short, often supply scientists with ways of looking at the world that complement purely logical and analytic modes. This cross-fertilization is common enough, and the insights yielded by applying artistic methods to scientific problems useful enough, that an increasing number of investigators are suggesting that for exploring the human dimensions and implications of science and technology, artistic methods may even be superior to scientific ones. Chemist Carl Djerassi, for instance, the inventor of the birth control pill, has begun writing 'science-in-fiction' in order to explore the ethical and social implications of the latest biomedical innovations in meaningful ways impossible through purely analytical discourse (Djerassi, 1990, p. 16). For the same reasons, Nobel-prize-winning economist John Kenneth Galbraith said of his novel *The Triumph* that it "is a story I have tried to tell before in articles and lectures. But it has occurred to me that maybe there are truths that best emerge from fiction" (Galbraith, 1968, p. 7). Physicist/musician Victor Weisskopf has suggested that, "Especially in human relations, a piece of art or a well-written novel could be much more revealing than any scientific study. In many respects, *Madame Bovary* is a piece of sociology—in fact, better sociology than much of what is done by aping the techniques and language of the natural sciences" (Weisskopf, 1977, p. 410). And chemist/poet Roald Hoffmann has warned scientists to beware of chavinism in their dealings with the arts: "One thing is certainly not true: that scientists have some greater insight into the workings of nature than poets" (Hoffmann, 1988, p. 10). In sum, these men are arguing that the analytical methods of the sciences are not the only possible methods for revealing truth, and that particularly in the human sciences, but perhaps in all sciences, the artist's approach may be more insightful than that of the mathematician. This is an interesting and potentially revolutionary message that bears serious consideration, especially when it comes from such accomplished scientists.

Arts Advance the Sciences

The thesis that the arts may provide insights beyond the methodological capabilities of the sciences comes from the fact that the artistic innovations often precede and make possible subsequent scientific ones. Examples are legion.

Alexander Graham Bell's first invention, multiplex telegraphy, resulted from his avocation as a pianist. He was playing a well-known parlor game of striking an 'A' and showing his party that only the harmonics of 'A' resonated; and similarly for 'B' and 'C', and so on, when it suddenly struck him that one could design a telegraph along similar lines. One could send multiple messages along a single telegraph wire if one sent one metaphorically in the key of 'A', another in the key of 'B', and so forth. His work on multiplex telegraphy was what led him to the telephone (Mackay, 1997, 9ff).

In an intellectually related innovation, professional musician George Antheil and actress Hedy Lamarr collaborated to create on of the most influential inventions of the last century: frequency hopping. Lamarr was married to a major munitions manufacturer in Germany before divorcing him and moving to the United States. She was aware that munitions such as torpedos were usually radio-controlled, but that it was relatively easy to jam the radio frequency by which control was maintained. She discussed this problem with Antheil, a polymath who not only wrote some of the most revolutionary music of the twentieth century (e.g. 'Ballet mecanique'), but also wrote about endocrinology, crime, and war. They realized that radio signals are like music: if one changes the radio frequency at which one sends a message, one keeps the same 'notes' within a message, just as one retains the musical message when one alters the key. But if one changes the 'key' (radio frequency) on a random basis, then the person trying to intercept or jam the message will have a very hard time doing so. Their invention is the basis for almost all secure communications, control systems, and anti-jamming devices currently in use worldwide (Braun, 1997).

A musical device also inspired one of the first heart pacemakers. Engineer Earl Bakken was looking for a way to create miniaturized regulators for the electrical output of apparatuses being designed to steady heart rhythms. Bakken found the answer in an already existing device, the electronic metronome that musicians had been using for years. Instead of generating a sound **or light**, as musical metronomes do, Bakken reconfigured his device to generate regular pulses of electricity to stimulate the heart. His company, Medtronics, became a leader in the development of the implantable pacemakers that are used today (Jeffrey, 1997).

Author: Sense?

Visual arts have also stimulated many scientific innovations. Hermann Rorschach, the Swiss psychiatrist who invented the well-known Rorschach ink blot tests, was also an amateur artist. The idea for ink blot tests came to him from a popular party game based on decalcomania, an artistic technique in which an image is transferred from one piece of paper to another, or within a piece of paper by folding it. For entertainment, people would drip a variety of colored inks or paints onto paper that was then folded and pressed. When the paper was unfolded, unexpected images were revealed. Rorschach noticed not only that people had a tendency to comment on what they saw in the ink blots, but that different people saw very different things that were suggestive of their personalities and problems (Larson, 1958). Thus, Rorschach's innovation resulted from taking advantage of a technique invented and popularized by professional and amateur artists.

Perceptual psychologists also owe many debts to artists. Those studying motion perception, for example, often rely upon the rotoreliefs of Marcel Duchamps. Rotoreliefs are a form of artwork based upon tops. If a spiral is painted on a top, it appears to move continuously, even though it actually has a finite length. A similar effect can be observed if a spiral is painted on a round platen and rotated on a record player. Duchamps invented very large platens that he painted with extraordinary patterns that create effects that still puzzle perceptual psychologists and are therefore useful in their research. One of the most intriguing is a double spiral that appears to spiral both in and out simultaneously (Sekuler & Levinson, 1977, p. 61). Another set of perceptual phenomena that have become a major focus of psychological reasearch are the size and space illusions invented by Adelbert Ames, a lawyer and artist. The most famous of Ames' innovations is the so-called 'Ames room' that creates the illusion that a person standing at one side of the room is a dwarf and a person standing at the other side of the room is a giant, when in fact they are the same size (Behrens, 1994).

Sometimes artists and scientists collaborate in an intricate dance of images. One example of such a dance was initiated by M. C. Escher, the famous graphic artist. Escher specialized in drawing impossible things, such as hands emerging out of a flat piece of paper drawing themselves. Roger Penrose, a mathematical physicist and amateur artist, visited an exhibition of Escher's work in 1954 and was stimulated to invent his own impossible objects. The result of his experimentation is the famous 'impossible tribar' a two-dimensional rendering of a three-dimensional triangle that appears to twist both forwards and backwards simultaneously. Roger Penros showed his tribar to his father L. S. Penrose, a biologist who also dabbled in art, and L. S. Penrose soon invented the 'impossible staircase', in which the stairs appear to spiral both up and down simultaneously. The Penroses' published their 'discoveries' in 1956 the *British Journal of Psychology* and sent Escher a copy of the publication as thanks. Escher then developed the artistic possibilities of the impossible tribar and staircase in ways that have since become famous not only in artistic circles, but as fodder for psychological experimentation (Ernst, 1992, pp. 71–80).

The impossible tribar was only one of Roger Penrose's artistic forays. Another was his invention of aperiodic tilings, which also owe a debt to Escher. A tiling is a pattern made out of repeating visual or design elements that covers a surface such as a plane or a sphere. A periodic tiling is one that does so using a regularly repeating pattern. Much of Escher's graphic work involved periodic tilings interpreted as birds, fish, and other animals. Penrose spent many years mastering the techniques of making periodic tilings like those popularized by Escher. But he tired of the regularity of the patterns and began searching for new possibilities (personal communication). One of these was aperiodic tiling. Aperiodic tilings are composed of a limited number of invariant shapes that nonetheless result in a pattern that never repeats. Penrose was one of the pioneers of this field. He says he created them mainly as an artistic puzzle. He later investigated the mathematical properties of them. Even more recently, after his artistic renderings were popularized by Martin Gardner in his mathematics column in *Scientific American* (Gardner, 1977), crystallographers realized that many metal alloys have structures that are described as aperiodic tilings (Peterson, 1985b, p. 188). Thus, an artistic hobby resulted in the discovery of novel structures that subsequently shed light on the nature of previously mysterious properties of metals.

Artists often invent novel structures that subsequently reveal unexpected properties of nature. R. Buckminster Fuller, working as an artist and architect, laid out an entire theory of structural stability based on tetrahedral forms that eventually led to his invention of the geodesic dome. Fuller claimed that this structure combined the least material to encapsulate the greatest space with the greatest stability. As such, he suggested that it would turn out to be a fundamental construct of nature. In fact, when virologists began to study the structures of spherical viruses, they turned to Fuller for help in solving the possible structures and soon discovered that most spherical viruses are geodesic domes, as Fuller had predicted (Fuller, 1965, p. 72). More recently, chemists have discovered that extremely stable carbon compounds, appropriately called 'buckminsterfullerenes', can be made that have geodesic structures, and similar structures are beginning to be discovered among biological macromolecules.

Almost as well known as Fuller's geodesic concept is his student Kenneth Snelson's concept of tensegrity, in which stable structures result from a juxtaposition of rigid pieces and elastic tensions to yield structures with great structural integrity. Snelson's tensegrity sculptures exist in major collections (e.g. the Smithsonian) all over the world and attracted a great deal of attention during the 1970s. Among those who became enamoured enough with tensegrity sculptures to build some of their own were biologists Steve Hiedemann and Donald Ingber (personal communications), who more than a decade later were to realize that the structures within cells that maintain their shapes have many similarities to tensegrity structures (Brookes, 1999, p. 43). The tensegrity theory of cell structure has captured the cover of *Scientific American* (Ingber, 1998, p. 48), and the new mathematics of tensegrity captured the cover of *American Scientist* (Connelly & Back, 1998, p. 142), once again demonstrating that artistic inventiveness can provide basic scientific insights.

Artist Wallace Walker has similarly galvanized solid geometry. While a student at the Cranbrook Academy in the 1960s, he was asked to make a three-dimensional object out of a sheet of paper only by folding and gluing it. The result was a complex donut that could be folded through its center hole to take on a kaleidoscopic variety of shapes. Walker's invention not only earned him a patent but also attracted the attention of Doris Schattschneider, a mathematician specializing in geometric objects. Schattschneider determined that Walker's paper sculpture was the first of a novel class of geometric objects, now called kaleidocycles (Schattschneider & Walker, 1977).

Another version of paper folding has also become the source of major mathematical innovations in recent years, and that is the ancient oriental art of origami. Mathematicians have recently discovered that the rules of origami embody (literally) a set of mathematical algorithms that determine whether an object can be created by folding, or whether it must be cut. This observation has opened an entirely new field of resesarch into what is being called 'plication' that is now yielding unexpected benefits (Hayes, 1995). A set of engineers at the Lawrence Livermore National Laboratory in Berkeley, California have recently invented a huge, foldable lens, many times larger than any lens heretofore created, for use in space laboratories (Anon., 2001). Other scientists have discovered links between origami and logic that may transform the way computers are designed and programmed (Cipra, 1998).

Novel structures are not the only ways in which artists contribute to scientific innovation. Some contributions stem from artistic observations. Since artists are trained to observe what other people overlook, they sometimes think about what other people never see. Leonardo da Vinci, for example, was the first to observe that a cross-section through the branches of a tree from the twigs down to the trunk will always conserve the same total area of wood. 'Leonardo's principle' as this observation is now known, is still a viable area of research in botany and engineering. The invention of the concept of camouflage provides another, more modern example. Ever since people began hunting, they undoubtedly noticed that animals tend to blend into their environments, but it was not until the 1880s, when a professonal painter of portraits and angels named Abbot Thayer looked carefully at nature through the eyes of an amateur evolutionist that anyone thought to question how this blending came to be. After more than a decade of visual experimentation, Thayer described the entire range of possible mechanisms by which camouflage might be expressed in nature (Maryman, 1999, 116ff).

Artistic techniques have also been the basis for scientific developments. One such technique is anamorphosis, meaning 'shape change', which derived historically from the discovery of perspective. Perspective drawing involves the mapping of a three-dimensional object onto a flat surface. Renaissance artists quickly realized that two-dimensional objects could also be mapped onto three-dimensional surfaces, including spheres, cones, and rods (Gardner, 1975). Such transformations became central to D'Arcy Thompson's *On Growth and Form* (Thompson, 1930, Ch. 17). and Julian Huxley's *Problems of Relative Growth* (J. Huxley, 1932, Ch. 4), both of which describe evolutionary and embryological processes as anamorphic distortions. Anamorphosis also underlies Wilder Penfield's and neurologist-artist C. N. Woolsey's studies of the motor and sensory mappings of primates onto the cortex of their brains, which yield the familiar 'homunculi' with their huge lips, hands and feet, and tiny bodies (Woolsey, 1978).

Another striking example of how artistic techniques inform science is the reification of logic in modern computer chips. The logic embedded in computer chips is actually a pattern directing electron flow. This pattern is drawn using techniques as old as drafting architectural plans and then shrunk using photographic techniques to produce a tiny template. This template is then used to transfer the pattern to silica wafers using methods adapted directly from silk screening and etching. Thus, the physical embodiment of logic as a functional image on a chip contains within it hundreds of years of artistic experience (Root-Bernstein, 2000).

Finally, the arts can foster scientific advances through the development of new aesthetics (Root-Bernstein, 1996). The use of pixels, false coloring, and abstractions provide three cases. The process of breaking a picture into discrete areas of color (pixels) was invented by pointillist painters such as Seurat. The technique of falsely coloring objects was invented by Fauvist painters. And abstract art, in which a single element of a complex phenomenon, such as its pattern, structure, or color, is chosen for selective description, was pioneered by Picasso, Braque and Kandinsky during the 1920s. Examine any scientific illustration carefully and you are likely to find one or more of these artistic techniques being employed to focus attention on one particular aspect of data. Without an excellent sense of history, it is too easy to overlook the artistic origins of many of the scientific tools we use for analyzing our results (Root-Bernstein, 2001).

Artscience and Innovation: The Future of Polymathy

Fortunately, there is growing understanding that art fosters science. Mitchell Feigenbaum, one of the pioneers of chaos theory, believes that understanding how artists paint will provide the cognitive insights necessary to do better science: "It's abundantly obvious that one doesn't know the world about us in detail. What artists have accomplished is realizing there's only a small amount of this stuff that's important, and then seeing what it was. So they can do some of my research for me" (Gleick, 1984, p. 71). Similarly, C. S. Smith, of MIT spent a lifetime studying oriental arts and crafts for the insight they gave him into metallurgy: "I have slowly come to realize that the analytic, quantitative approach I had been taught to regard as the only respectable one for a scientist is insufficient . . . . The richest aspects of any large and complicated system arise from factors that cannot be measured easily, if at all. For these, the artist's approach, uncertain though it inevitably is, seems to find and convey more meaning" (Smith, 1978, p. 9).

In fact, some scientists are formally inviting artists to help them perceive new realities. Milton Halem, chief of the Space Data and Computing Division at NASA's Goddard Space Flight Center in the early 1990s, invited Sara Tweedie, a design instructor in the Corcoran School of Art, to help his engineers invent new ways to visualize the huge amounts of data being generated from satallite sources. "Visualizing that data, coloring that data, enables the mind to more quickly assimilate the information and the image", he noted. He says he needs artists such as Tweedie to push "modeling a step beyond where it's gone in the past" (Mercier, 1990, p. 28). The National Supercomputing Facility and Bell Laboratories (now Lucent Technologies) have hired artists for similar reasons.

But the real future of sciences–arts interactions must be within the minds of individuals. Artists and scientists too often speak different languages and use different tools. In order for them to collaborate effectively, to perceive in each others' problems and methods opportunities for insight, we must have a large cadre of artist-scientists and scientist-artists. Some of these people already exist. Desmond Morris for his part refuses to be labeled as a scientist or an artist: "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, 1987, p. 27). He adds that, "perhaps the time will come when we will give up the folly of separating sub-adults into the imaginative and the analytical—artists and scientists—and encourage them to be both at once" (Remy, 1991, p. 18).

This melding of the artistic and scientific mind within a single individual may even have benefits for both since, as the art critic Kenneth Clark has suggested, art and science emerge from the same imaginative sources: "Art and science . . . are not, as used to be supposed, two contrary activities, but in fact draw on many of the same capacities of the human mind. In the last resort, each depends on the imagination. Artist and scientist alike are both trying to give concrete form to dimly apprehended ideas" (Clark, 1981, p. 24). Rather than forcing individuals to choose a scientific approach to problems or an artistic one, thereby devaluing the other, Clark admonishes us, to "wait patiently for our faculties to be reunited" (Clark, 1981, p. 29).

Clearly, the arts and sciences are as capable of full integration today as they were in the Renaissance, and there is every reason to expect their union to be as fruitful. But to derive the fruits of their union, we must foster the connections and the people who can make them. Richard Mueller, an MIT-trained engineer, novelist and artist agrees with Clark. He writes in his stimulating book, *The Science of Art*, "In many ways, I think, the scientist is delaying his own understanding and development in science by discouraging, not only the artistically inclined members of his clan, but also the artistic urges within himself . . . . Art may be a necessary condition for constructing the new consciousness from which future science gets its structural realities to match nature, in which case it is more important than we generally admit . . ." (Mueller, 1967, p. 320).

Thus, we need a new kind of education that fosters interactions between disciplines rather than divisions between them and which trains people who can bridge C. P. Snow's 'Two-Cultures' divide. We need such curricula and people not only because of the fragmentation of knowledge that must result in their absence, but more importantly as a stimulus to the highest forms of innovation. For specialization can never suffice. As General Electric engineer, Charles Steinmetz, pointed out nearly a century ago, "technical training alone is not enough to fit a man for an interesting and useful life" (Seymour, 1966, p. 119). He urged his students to study languages, literature, philosophy, art, music and history, arguing that if an engineer failed to produce a workable invention, it was his own fault for not understanding the greater needs of society and the factors that control its manufacturing and economic functions. Similarly, composer-architect-engineer Iannis Xenakis argues today that "the artist-conceptor will have to be knowledgeable and inventive in such varied domains as mathematics, logic, physics, chemistry, biology, genetics, paleontology . . . the human sciences and history; in short, a sort of universality, but one based upon, guided by and oriented towards forms and architecture" (Xenakis, 1985, p. 3). All this is necessary so that we can address the truly important problems of the world, added embryologist and art historian C. H. Waddington: "The acute problems of the world can be solved only by whole men (and women), not by people who refuse to be, publicly, anything more than a technologist, or a pure scientist, or an artist. In the world of today, you have got to be everything or you are going to be nothing" (Waddington, 1972, p. 360). Buckminster Fuller agreed: "Overspecialization leads to extinction. We need the philosopher-scientist-artist—the compherensivist, not merely more deluxe quality technician mechanics" (Fuller, 1979, p. 104).

To invent and to create requires an understanding that incorporates all that is known sensually and abstractly, subjectively and objectively, imaginatively and concretely. And because of their wide disciplinary training in the imaginative skills, handicrafts and expressive languages, only polymaths will have the tools necessary to do so. Thus, the future of innovation will reside, as it always has resided, in the minds of mulitply talented people who transcend disciplinary boundaries and methods. We can recognize this phenomenon by fostering artscience—a term promoted by artist-inventor-psychologist Todd Siler (Siler, 1990)—or we can retard it by creating educational and workplace systems that prevent arts and sciences from meeting. As Siler has pointed out, artscience is both the past and future of innovation because innovators cannot help drawing upon any form of thinking that will spur their imagination. We ignore this profound truth at our peril.

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