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The concepts of beauty and creativity: Earth science thinking

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ABSTRACT

The concepts of creativity and beauty have been intertwined for centuries and have been examined by both artists and scientists. This is a personal essay reflecting on the nature of creativity, its manifestations in artists and scientists, and the challenge of maintaining creativity as we age.

Keywords: creativity, beauty, art, science.

INTRODUCTION

Like other authors in this volume, I am an earth scientist—one who came late into the earth sciences by way of a musical training in public schools, a physics and mathematics background from a liberal arts college, and a Ph.D. in planetary sciences from a technical institute. Music has been an integral part of my life since childhood: as a performer, student, and amateur composer (Fig. 1). This is a personal essay written over the past 15 years during which I have reflected variously on these elements of my life (music, physics, mathematics, earth and planetary sciences, liberal arts, science in general); on problems with identifying and preserving creativity; on the role of institutions and our working ambiance in nurturing or harming creativity; on the evolution of creativity with age; and, especially, on explaining scientific creativity to nonscientists. I have concluded that concepts of creativity and beauty are similar in the sciences and arts, but that the development of specialization and abstraction in both science and art within Euro-American cultures has made communication difficult. Recognition of similarities in our creative endeavors, in turn, and study of the long-lived composers and poets have led me to some ideas for prolonging and enhancing creativity.

The concept of beauty is often associated with creativity. For centuries, humans have thought and written about the relation between the two, and it is difficult to write about these subjects without being obvious and trivial, or pedantic and dilettantish (Chandrasekhar, 1989). My thinking is very much influenced by my life in a western, Euro-American twentieth-century culture, and this essay should be read with that context in mind. Generalizations beyond this culture are not valid.

Much of this essay is about communication between scientists and artists, and it may read as if all scientists, artists, and people were involved in the discourse. Unfortunately, that is not true. Not all humans think about creativity and beauty. Not all think about art and science. Not all will incorporate art and science into their lives. Communication requires both eloquence in expression, and open minds in reception.

There is no "right thinking" about creativity or beauty. This essay is my thinking on this subject at this time in my life. It was begun in 1990 as I was thinking about how the major institutions in which most scientists work could nurture creativity. That thread of thinking always dead-ended in a self-serving whine. The editors of this volume redirected the focus toward examination of earth science thinking. I suspect that if I started another essay right now (mid-2006), I could not re-create the current one. A new essay would be quite different, especially if it took another 15 years to complete. Similarly, I know that if I tried to "re-create" the composition in Figure 1, I would now create something quite different…or not even feel creative about the elements that it represents at all. Such is the ephemeral, vague, whimsical, and ill-defined nature of "creativity" and "beauty," the subjects of this essay.

My thinking on these topics was crystallized by a paper "The Perception of Beauty and the Pursuit of Science" by the astrophysicist Subrahmanyan Chandrasekhar (1989). Chandrasekhar had spent approximately two decades studying the lives of poets

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9.77 seconds

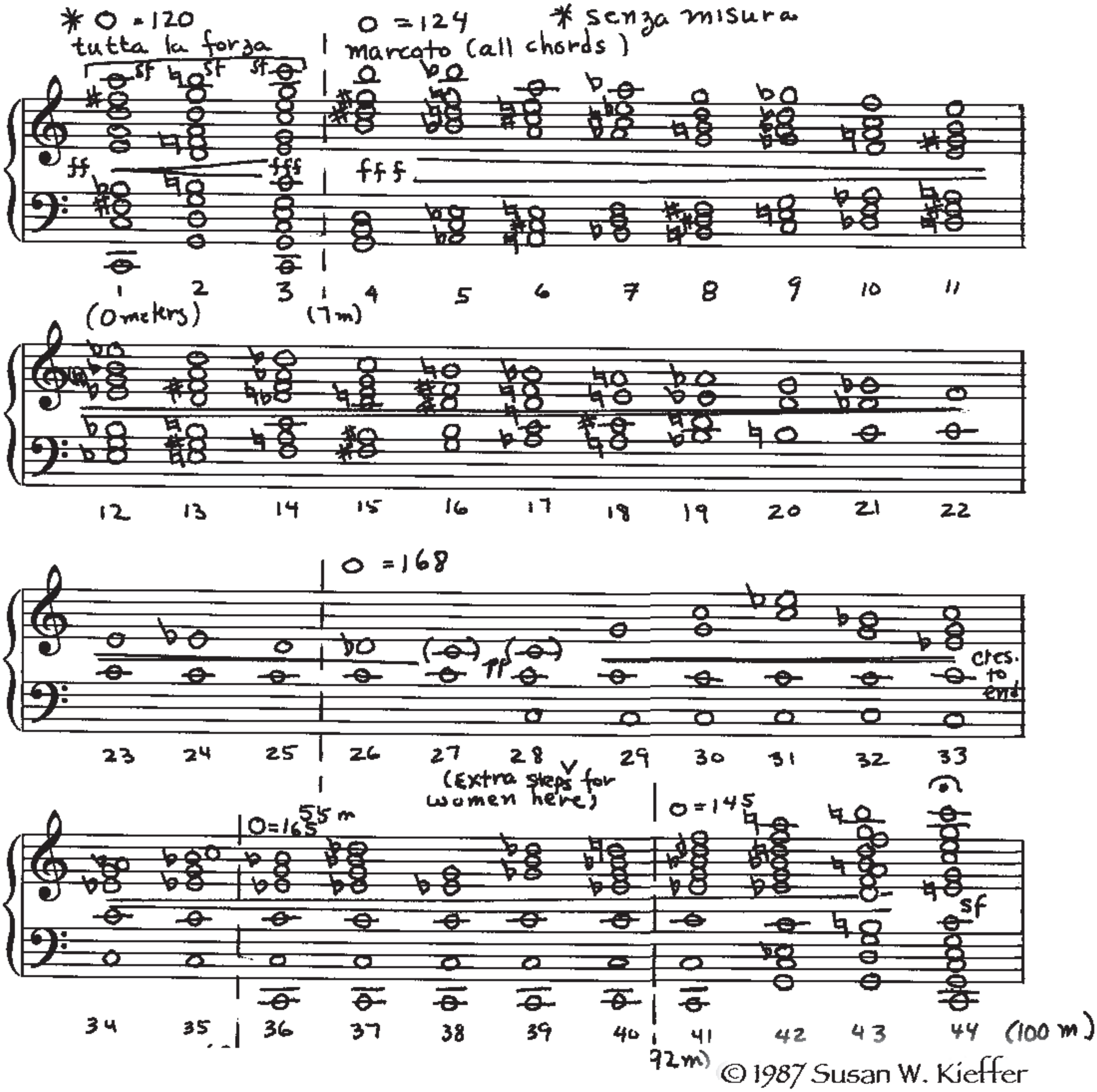

Figure 1. The score for a musical composition titled “9.77 seconds.”

and scientists, and his conclusions were based not only on biographies, autobiographies, and literature on creativity, but also on personal acquaintance with famous contemporaries. His conclusion was that there is a real difference in the longevity of creativity between scientists and artists—namely, that creativity was the preserve of the young in science, but that artists preserved, or increased, their creativity with age. He felt that the difference between artists and scientists was "the apparent inability of a scientist to continuously grow and mature" (Chandrase khar, 1989, p. 27). (Interestingly, and I will assert, relevantly, he was generally comparing twentieth-century physicists and mathematicians with nineteenth-century literary and musical artists.) The social, political, and economic contexts within which much of science has been done in the twentieth century are very different from the environment of art or science in the nineteenth century. Specifically, both art and science were nearly a cottage industry in the nineteenth century—done in small clusters with a form of patronage very different from twentieth-century (and now, twenty-first century) science.

I started wondering if Chandrasekhar's discouraging conclusions were true, and, if so, how and if they applied to earth and other natural scientists. (I will restrict myself to discussing the earth sciences from here on.) Our largely inductive and tangible science is quite different from the more analytical, deductive, abstract sciences. Rather than relying purely on analysis and deduction, our thinking in the earth sciences also builds cumulatively on experience and induction. I asked myself: are earth scientists perhaps more like nineteenth-century artists than other twentieth-century scientists?

In this essay, I will (1) adopt definitions of beauty and creativity; (2) compare creativity and beauty in the arts and sciences; (3) discuss a hypothesis that the perceived schism between the arts and sciences arose in western cultures when abstraction and specialization developed and communication became difficult; (4) examine the role of aging in creativity; and (5) speculate on how individual earth scientists might prolong their creativity.

There is always risk in generalization and stereotypes—for example, regarding point 3, I have many colleagues in physics who will point to the anecdotal evidence of a correlation between physics and musical talents. Indeed, I have been the recipient of their invitations to participate in many soirées, so they might not appreciate the thoughts in this essay at all. So be it…we all understand exceptions to rules.

I came to admire the Nobel Prize–winning physicist Hideki Yukawa (1907–1981) very much as I worked on this essay. In reading Yukawa's essays, I felt as if I was sitting beside him in an easy conversation. It was a great surprise to have read the philosophic parts of his work and, only then, discover that his father was a geologist-geographer in Japan at the turn of the century. Having myself traveled in Japan with Japanese geologists, I instantly wondered about this father and his influence on Yukawa. As a young man, Yukawa perceived his father as a physically vigorous adventurer—traveling all over the country preparing geologic maps, surveying, going into the mountains and places that were inaccessible "all involving a considerable amount of physical strain and even a certain amount of danger" (Yukawa, 1973, p. 25).

Yukawa saw none of those qualities or desires in himself. Furthermore, his father had the task of finding lodging in the mountains, a task "that required considerable contact with all kinds of people." Yukawa apparently viewed the prospect of finding and staying at a completely unfamiliar inn to be extremely frightening, and he decided that geology and geography involved the closest kinds of exchanges with human beings, and that while he was not antisocial, he was certainly asocial. Thus, he chose to go into physics by progressively eliminating the natural sciences (because they were too social), engineering (because it was both social and involved too much haggling over the prices of machines), and the social sciences ("because he had no interest in them at all"). This left him physics and mathematics. His success in these fields is perhaps a testament to his self knowledge and the elimination process by which he chose his life's work.

It is remarkable, however, that he came nearly full circle as he analyzed creativity later in his life. He emphasized the need to maintain close contact with the natural world to preserve creativity. To Yukawa, the awareness of nature, in a much more intuitive way than most westerners would accept as a part of scientific thinking, appeared to be a vital ingredient in creativity. He felt that not only his own success in moving theoretical physics a step further owed something to this way of thinking, but that an element of it can be seen in such creative acts as Heisenberg's formulation of the uncertainty principle. While accepting the fact that his later mental struggles to discern the nature of particles did not lead to any breakthrough, he expresses the conviction that "an Oriental approach" (his words)—briefly summarized by the definition of beauty used in this essay—is a better way to deeper understanding than the present pursuit of ever greater detail with an ever greater mass of facts and theories. I will conclude that it may be this contact with the natural world that allows geologists to grow and mature with age.

BEAUTY AND CREATIVITY

The concept of "beauty" is subjective, but has often been associated with creativity, and although one usually finds essays in which creativity is defined first, I found it more logical to define "beauty" and then "creativity." Much has been written for millennia about "beauty." Different scientific disciplines would probably advocate different definitions, such as "a sense of symmetry," a "theory with a minimum number of assumptions," "generality of paradigm," "predictive power," or "conformity to Occam's Razor." In this volume, Don Anderson discusses the role of simplicity and Occam's Razor in how we should evaluate the ideas of plate tectonics. Artistic disciplines would have perhaps as many other definitions, and different cultures yet others.

Of the many definitions of beauty and creativity in the literature, I chose the following:

Beauty: the "proper conformity of the parts to one another and to the whole" (an ancient definition, but possibly first explicitly given in the context of the "exact sciences" by Heisenberg, 1971).

Creativity: the ability to form or formulate something that no one else has done before, and that feels as if it has the proper conformity of the parts to the whole, i.e., the ability to formulate something that feels beautiful.

This is a personal essay, not a treatise on philosophy or aesthetics, and I do not feel compelled to define every word, including "proper," or "art," or "science," but will try to imply relations as I write. For example, it is difficult to define "proper" in this context, but it is relatively easy to define what is not proper: evil, false, forced, misleading….

By implication, Richard Feynman (as cited in Don Anderson's essay) defined "proper" in this way: "You can recognize truth[1] by its beauty and simplicity…when you get it right, it is obvious that it is right" (Feynman, 1965, p. 171).

Or, Buckminster Fuller on working on a problem "…when I have finished, if the solution is not beautiful, I know it is wrong."

The concept of beauty certainly varies from person to person and, in science, from discipline to discipline. Bodies of knowledge tend to grow and become cumbersome and complex for lack of a framework, or because the framework is wrong. Perhaps in common to all of the disciplines, beauty implies elements of simplification and unification. The concept of beauty as used in the sciences often places abstraction in a valued position, but as we examine the different scientific disciplines, we realize that the processes of abstraction, deduction, induction, and intuition all play different roles. The concept of beauty varies significantly with the proportion of these components. In mathematics, beauty may be associated with deduction and rigor; in geology, with induction and breadth. In detail, it could become as difficult to find an agreement on the concept of beauty amongst scientists as it is across the arts and sciences, but I believe there would be general agreement that in some way "beauty" is found in the relationship of parts to each other, and to the total.

How does one define creativity[2]? The lives of many creative people show evidence of internal feelings of struggle, which I feel were eloquently summarized by Yukawa (1973, p. 131–132):

> "Without some contradiction within oneself, there can be no study; that, indeed, is the essential nature of study. To put it differently, one has some place that is dark, or obscure, or vague, or puzzling within oneself, and one tries to find some light in it. Then, when one has found a ray of light, one tries to enlarge it little by little so that darkness is gradually dispelled. This, I feel, is the typical process whereby creativity shows itself."

In scientific research, a worker may get a feeling that he or she has had a creative insight, but would be at loss to describe just how that insight arose, or even why it feels creative or beautiful. Rather, one just has a feeling that something unexpected has taken place, and that it is beautiful in the above context, that is, you "get it right."

CREATIVITY IN SCIENCE AND ART

Communication of concepts, whether scientific, aesthetic, concrete or abstract, seems to be a fundamental drive of humans. The means of communication, however, differ amongst individuals, cultures, disciplines, and generations. These differences are at the root of many misunderstandings, and they present a continuing challenge to all humans.

Scientists have a goal of formulating hypotheses within the methods of science, of seeking to falsify these hypotheses, and of revising them or further testing them. Our goal is to purposely eliminate ambiguity and unclearness. To achieve this goal, scientific language has evolved almost into a new language, too commonly intelligible only to a small community of specialists.

Nevertheless, a measure of our success with science is the creation of a body of knowledge by scientists from different generations, cultures, languages, political views, and religions. The communication of the view of the world that is accessible by scientific methods is a creative feat comparable to the transmission of human aesthetics in the arts through different centuries, cultures, and languages. The mathematical sciences—math and physics—have long held prestige as the most "beautiful" of the sciences, precisely because they are the least ambiguous, most rigorous of all the sciences (see further discussion of this in chapter 8 by Dodick and Argamon). Yet we earth scientists can hold up our tremendous successes in also communicating the concepts of space, time, stratigraphy, and process through different cultures and languages. The scientific product—although very different in expression from the artistic product—resembles the arts

[1]This is an interesting comment from Feynman, because, taken in isolation, it implies that he believed that science could prove "truth." In fact, all we can do in science is prove something is false, which Feynman discussed extensively in this same reference. We do, however, use terms like "truth" or "laws" to refer to ideas that have withstood many tests of falsifiability. In this sense, our use of these words has different meanings from other nonscience parts of our culture. This has become increasingly obvious in the debate of the past decade within the United States over the roles of science and religion in the origin and evolution of humans. Thus, Feynman's quote is appropriate within our scientific context, but taken out of context, could be misleading about the nature of science.

[2]Creativity is difficult to define and to measure. Productivity is often used as a measure of creativity. The definition of "to produce" in (Webster's II, 1984) is rooted in the Latin words: "pro"= "forward"; "duce" = "to lead." Thus, definitions of the verb produce are: (1) to bring forth: yield; (2) to create by physical or mental effort; (3) to manufacture; (4) to give rise to; (5) to bring forward; exhibit; (6) to sponsor or present to the public (as in a musical production); (7) ...etc. Productivity in our modern world, especially the academic world, has lost some of its subtle meaning as based in the Latin roots of "to lead forward." Productivity has much more the context of "to manufacture" or "to exhibit" (i.e., "publish or perish"). I will try to distinguish between productivity and creativity in this essay.

in that it accomplishes communication between human beings across generational and cultural gaps.

When scientists are writing or conversing about their work, they ultimately aim to communicate one thought at a time clearly and unambiguously. In that particular sense, in this essay, I am striving to be linear and "scientific," even though the subject is philosophic. I am trying to communicate one thought at a time, and to progress in an orderly way toward conclusions.

The goal of communicating unambiguously and clearly does not mean that we scientists always think that way: in fact, the fundamental drive toward creativity and new ideas seems to be, as Yukawa said, ambiguities or inconsistencies in our perceptions of the world. If there were no ambiguities, we would have nothing to struggle with. Our internal struggle is to reconcile and get rid of inconsistencies. But, the processes by which scientifically creative ideas arise can often be completely different from the processes by which we test, verify, and modify these ideas.

In contrast to our scientific striving for unambiguous expression, artists seem to purposely strive for simultaneous communication on many levels. Great literature, music, dance, performance, and paintings all project out to us on many levels—direct and indirect, public and private, actual and symbolic, objective and subjective. Aldous Huxley described art as seeking to provide an experience rich in harmonics and overtones.

The short piece of music in Figure 1 is an example of artistic, rather than scientific, communication. It may mean nothing to some people, just as some scientific communications and some art works mean nothing to some people. It may, or may not, seem linear; it may or may not invoke sounds, images, color, or even, smells. It may mean more to you, or less, after you read the intent of the piece described in the appendix. It is not, however subject to any tests of falsifiability or reductionism, as would be required of a scientific figure.

If I could take some liberty and propose a generality based on my own experience, I would say that scientists live internally with fundamentals, harmonics, overtones, and dissonances, but strive to seek and sort out the fundamental from the harmonics and overtones. Artists, on the other hand, have the liberty of portraying all of these simultaneously. Because of this difference, although scientists and artists may agree on the general concepts of creativity and beauty, we have trouble recognizing this agreement in expression. I think that this difference in perception, interpretation, and communication of world views is at the root of some of the problems that we currently have in perceiving the relations among art, science, and individual lives.

It is worth reviewing briefly how and when the perceived gap between the arts and sciences arose, because it bears on the apparent difference in longevity of creativity amongst us, and on possible reasons for difficulties that both artists and scientists are having in initiating and/or prolonging their creativity in the twenty-first century. In much of western society over the past few hundred years, explicit and implicit communication between artists and scientists has become more difficult because both the sciences and the arts have become increasingly abstract and specialized. This is the so-called "schism" between the arts and sciences, the perceived "two worlds" of C.P. Snow (1959). Are earth scientists affected by this schism? Certainly yes. Are we affected as much as some other sciences? Possibly not.

If we look back to ancient Greece or to other cultures from eastern Asia, Africa, the Americas, or aboriginal Australia, we can find harmony and balance in the use of intuition and abstraction in the perception of the world. In ancient Greece, scientists appreciated poetry, poets appreciated geometry, and the world had a unity and comprehensibility to individuals. Music was perceived as organic to the soul, e.g., the Greek attribution of moods, character, and morality to their modes. Indeed, if we look back only as far as the life and philosophy of Thomas Jefferson, as reflected in the American Constitution, we can find a unity of science, philosophy, literature, and the arts that has largely disappeared in the modern western world. Until approximately the Victorian age, there was relatively little debate that creativity or the perception of the world or beauty might differ in the arts and sciences. The available science and arts were rather easily incorporated into the lives of thoughtful people.

But the roots of the schism between art and science were in place in those parts of the world where science was about to explode into abstraction and specialization. In his autobiography, Darwin tells how he became afflicted by "a curious and lamentable loss of the higher aesthetic tastes" (Darwin, August 1876). He would get so bored trying to reread Shakespeare that he would get physically ill. On the other side of the schism, the young poet Keats drank a toast (possibly after many, many other drinks!) in hopes of destruction of Newton, who had explained the "science" of the rainbow and had thus robbed it of its poetry. Even if Keats wasn't serious, his quote has not gone without serious notice; viz. Dawkins (1998) published a long book on the relationship between arts and science based on this quote of Keats.

However, in between these extremes, many have labored and written to find a middle ground, to reconcile thought processes, perceptions, and values—those general things that we believe are associated with creativity and aesthetics. T.H. Huxley, a great friend and champion of Darwin, advocated a primarily scientific education tempered with lots of humanities and classics, all of which he loved. Mathew Arnold, on the other hand, believed in a humanistic and classical education tempered with enough science to allow people to understand the world around them. Wordsworth, even though enamored with the poetry of rainbows, nevertheless was also able to admire Sir Isaac Newton.

Even the first great revolution in physics, initiated by Galileo and completed by Newton, did not complete the isolation of western science from philosophy. Abstraction began to play a more prominent role in the evolution of science with Newton's work, but concepts of space and time still accorded with intuition, and the new abstractions being introduced were directed toward problems that humans could comprehend—orbits of planets at a scale perceptible on a clear night, and the fundamental fact that we all fall down.

However, with the second revolution in physics, which included Planck's and Bohr's quantum mechanics and Einstein's theory of relativity, abstraction became a dominant process in science. In a sense, abstraction became more concrete. Einstein's four-dimensional space-time world became an intuitive reality to a new generation of physicists and became a new starting point for more abstraction. And even the physical manifestations of the theory—such as perturbations of planetary orbits—became too difficult for individuals (including many scientists) to easily understand intuitively. As a freshman entering a liberal arts college, I learned Kepler's law of planetary orbits while lying with fellow students and instructors on the grass by our small observatory watching the nightly changes in the sky. As a senior majoring in physics and mathematics, I struggled with a capstone thesis trying to understand Einstein's view of the orbit of Mercury. I did not have the same "gut-level" experience of understanding that I had with Keplerian orbits.

Atomistic concepts also became more abstract. From the time of Aristotle through the early twentieth century, scientists struggled with trying to reconcile matter versus void, atomic versus continuum properties of matter, and wave versus particle nature of light. For a long time, most scientists and intellectuals could at least intuitively relate to the problems and questions. However, in the age of new science, not only the general public, but many scientists feel estranged from a good fraction of the body of scientific knowledge. In specialization, scientists have developed their own vocabulary, and it is a vocabulary that is nonintuitive, where new words are invented as new discoveries arise (viz., quarks), or old words are given new meanings, accessible only to the inner circles (viz., charm, strings).

Not quite, but nearly, in parallel, art became more abstract. The modality of the ancient Greeks was preserved for a long time through the baroque and romantic composers, but diverged in the twentieth century, e.g., into the12-tone patterns of Arnold Schoenberg, the chance music of John Cage, or the many forms of electronic music. Although it intermittently reconverges (e.g., into jazz), divergence has been the general trend. Poetry evolved from the classical rhythmic forms into many schools of modernism, and moved away from classical realism to the many forms of modern expression. Aesthetics became more specialized.

However, to the extent that all humans live on planet Earth, the great revolutions in geology have not isolated us from other scientists or from the public as much as the discoveries in physics and mathematics have caused isolation. Except where we adopt the most modern and complex tools of modern physics, chemistry, and biology, our earth and planetary science concepts remain relatively accessible to our colleagues and the public. Our great paradigm shifts—the invention of the map, stratigraphic concepts of time, plate tectonics—are easily appreciated by an inquiring mind, and, with the few exceptions of our time-scale nomenclature and our mineral and rock names, the concepts and words (in English) retain the general context of their origins. In this way, in spite of all of our technical sophistication, I do believe that twentieth- and twenty-first-century earth scientists are more like nineteenth-century artists than other modern scientists.

CREATIVITY, BEAUTY, AND THE EARTH SCIENCES

As a community, earth scientists do not have a historic legacy of thinking about our creativity like the mathematicians and physicists. In fact, this Geological Society of America (GSA) publication is quite unique in asking questions about earth science thinking. Furthermore, in the current intellectual climate, and with the large numbers of scientists in the world today, there are few measures of creativity. We measure productivity, not creativity. Evaluation of creativity requires a value judgment, not simple numerical counting, or even measures of "impact." In the context of this paper, it requires a judgment of beauty. Perhaps as a community, we need a new form of peer evaluation, essays that define and discuss creativity and the contributions of individuals within that context.

Take the following premise: a geologic map, well done, is certainly beautiful. William Smith did not produce the first geologic maps (George Cuvier and Alexandre Brongniart published a geologic map of the Paris Basin in 1808), but he was the first to publish a map that "got it right" (1815). Smith understood that not only was there order in the geologic strata, but that fossil contents were in the same order, and that order was preserved over a very large geographic area. This was a creative leap that introduced a dimension of time to biology and founded the historical science of life on Earth.

The concept of geologic time is beautiful. James Hutton (1726–1797) and Arthur Holmes (1890–1965), who had the ideas of relative and absolute deep geologic time, respectively, were creative. Hutton was a deeply religious man living in a time when many believed in a young Earth, and when the neptunist ideas of Werner prevailed. Driven by his theological belief that a beneficent God had put the world here for humans, Hutton developed his plutonist concepts and came to the scientific conclusions that the world was very old. His beliefs propelled him to assemble evidence about the importance of intrusions and metamorphic rocks, an interesting mix of theology and geology. Holmes, a century later, was able to take his knowledge of physics into geology to give us the first accurate ages of the Earth and our eras and, later, to give us a remarkably accurate theory of plate tectonics—~30 yr before data became available to back up the theory.

The concept of plate tectonics is beautiful. The founders of plate tectonics were creative, e.g., Holmes mentioned above, Harry Hess who was able to take his experience as a geologist and Navy submarine commander to propose seafloor spreading, and J. Tuzo Wilson (1908–1993), who proposed hotspots to account for oceanic volcanic island chains and who discovered transform faults.

The concept of geology on other planets is beautiful. Eugene Shoemaker (1928–1997), the founder of astrogeology, stole the planets from the astronomers and gave them to the geologists by advocating that terrestrial geologic mapping techniques be applied to the surfaces of other planets. Shoemaker's lifelong work on the dynamics of meteorite impact, the science of relative dating the surfaces of other planets by counting impact craters, and advocacy of "catastrophic" impact processes in the intellectual climate of uniformitarianism were creative endeavors.

Many other individuals could be cited in such an exercise. These particular examples were chosen because of the longevity of their creativity.

CREATIVITY AND AGE

Creativity tends to manifest itself in youth, but that is not the topic of this essay. Rather, it is "what happens to creativity with age?" Chandrasekhar (1989, p. 14) borrowed from T.S. Elliot to say how he was going to address this topic: "one can always save the subject by magnificent quotations." A few well-chosen quotes can illustrate the direction of Chandrasekhar's thinking:

> The rule that a poet is at his best after the age of 30 might have applied as well to [Shelley] as to Shakespeare, Milton, Wordsworth, Byron, Tennyson, and indeed almost every major English poet who lived to be over 30. [Desmond King-Hele on the death of Shelley at the age of thirty.]

> One of the most significant facts, for the understanding of Beethoven, is that his work shows an organic development up until the very end. The greatest music Beethoven ever wrote is to be found in the last string quartets, and the music of every decade before the final period was greater than its predecessor. [J.W.N. Sullivan]

> And, then about scientists:

> A person who has not made his great contribution to science before the age of thirty will never do so. [Einstein]

> Age is, of course, a fever chill
> that every physicist must fear.
> He's better dead than living still,
> when once he's past his thirtieth year!
> [Dirac]

> No mathematician should ever allow himself to forget that mathematics, more than any other art or science, is a young man's game....Galois died at twenty-one, Able at twenty-seven, Ramanujan at thirty-three, Riemann at forty. There have been men who have done great work later;...[but] I do not know an instance of a major mathematical advance initiated by a man past fifty...A mathematician may still be competent enough at sixty, but it is useless to expect him to have original ideas. [G.H. Hardy]

> A man of science past sixty does more harm than good. [Thomas Huxley]

As Chandrasekhar says "I do not doubt that these statements will be challenged or at least subjected to qualification." However, as I searched both the literature, and my own experience, to find proof that these statements were generically wrong or had been applied to special classes of scientists (mathematicians and physicists seem especially hard on themselves!), I began to find more and more anecdotes and statistics that reinforced Chandrasekhar's conclusions given in the introduction to this paper.

Yukawa offers a reason that creativity may be the province of the young in science. Within the sciences, creativity requires a breaking down of fixed ideas—internally within a person, scientifically within a discipline, or institutionally within a community. It is not easy to break down internal frameworks.

> A considerable period of preparation is necessary before a particular man can display creativity in a particular field and in a particular form. He must, in short, have acquired all kinds of knowledge and also, probably, undergo all kinds of training. It is only after many kinds of prior conditions have been satisfied that creativity can show itself. By the time that one has done research for a long continuous period and become a full-fledged research worker, one has developed within oneself a relatively stable system of knowledge. This system of knowledge has been integrated by one's own efforts into a particular, definite form. And this business of integrating by oneself is, of course, an extremely valuable experience in itself. It means that one is able to teach others, and to pass on one's own knowledge.

> That state of affairs also means, conversely, that one has become set in one's way of thinking. To exaggerate a little, one has become a mass of fixed ideas.

> To know a lot of things has the advantage that, in theory at least, it serves as a basis for discovering new things; but it also has a gradual immobilizing effect. Whatever happens, nothing surprises one; and the chances for a display of creativity are lost. (Yukawa, 1973, p. 125)

What about earth scientists? Referring to those whom I cited above, we find evidence of prolonged creativity. William Smith colored in the first geologic map in the world in 1799 at the age of 30 and became the founder of English, and indeed, modern geology, by publishing his famous map in 1815 at the age of 46. He developed the concepts and some of the vocabulary of the field of stratigraphy until he died. James Hutton had the idea of deep time and found evidence to support it later in his life when he was 62 (1788). Arthur Holmes pioneered geochronology at the age of 21. He is lesser known for his radical, and eventually proven, theories on continental drift. He embraced this concept because his work on radioactivity, geological time, and petrogenesis had given him an unusual insight into understanding processes in Earth's interior. He was the first to propose that slow-moving convection currents in the mantle caused continental breakup, seafloor formation, crustal assimilation, and continental drift. He had these ideas at a very young age, but developed them continuously for over 30 yr until his death. J. Tuzo Wilson, a Canadian geophysicist, had his stunning insight into the nature of plate tectonics at the age of 50, a mental leap that caused him to refute his own ideas of earlier years. From that time until his death, he contributed inspirationally and eloquently to the new paradigm. Wilson's observations of the Canadian Shield were seminal in his ideas. Eugene Shoemaker's remarkable career grew and grew and showed no signs of slowing down until he was tragically killed in an automobile accident at the age of 69.

No two careers have followed the same pattern, but there is a remarkably consistent theme that the great careers in earth sciences were grounded in a very tangible relation to Earth and observations of it. Through our profession, we are connected to the every day experience of living on this planet, and we are sustained by it in our work, as well as in our lives.

LESSONS LEARNED

Chandrasekhar (1987) pondered why Lord Rayleigh had such a prolonged career compared to Maxwell and Einstein, and he found a hint of the answer in the memorial address given by J.J. Thompson for Lord Rayleigh in Westminster Abbey, December, 1921:

> "There are some great men of science whose charm consists in having said the first word on a subject, in having introduced some new idea which has proved fruitful; there are others whose charm consists perhaps in having said the last word on the subject, and who have reduced the subject to logical consistency and clearness."

Yukawa concluded that it seems absolutely essential that in order to maintain creativity, we have to move periodically out of our own masses of fixed ideas into the unknown. Balancing newness with wisdom is a challenge. In the earth sciences, we have the opportunity to do this simply by exploring our planet, and now, other planets. We must recognize that stimulus and surprises are important. We as individuals should try to break down the barriers that our own frameworks erect and allow ourselves to be open to surprises.

Finally, we should recognize that failure does not always mean a lack of creativity. Some of the greatest and most creative of earth scientists had some major failures, e.g., J. Tuzo Wilson had to discard his old views on tectonics at the age of 50 when the new information relevant to plate tectonics became available. We should learn to reward creative failure nearly as equally as creative success. Most people do research for about forty years. Some may go through life feeling that they have had no successes, most would hope to a few successes, and few would claim continuous success. What are we doing all of that time that we are not successful? Probably about the same thing that Beethoven or Shakespeare did when they wrote and rewrote. We are certainly not doing nothing. We are doing something (a reviewer suggested "composting," "sifting," "simmering"), even if we do not later count it as successful. We get up in the morning, work hard from dawn till dusk, and throw much of what we have done into the wastebasket in despair. The line between a beautiful success and a beautiful failure is nearly invisible.

APPENDIX: EXPLANATION OF "9,77 SECONDS, FOOTSTEPS TO A WORLD RECORD" (FIGURE 1)

The world record for the men's 100 m dash was 9.83 s when I composed this piece in 1987. At the time of submission of this manuscript in 2005, that particular men's record had been disallowed; the current world record was set in 2005 by Asafa Powell at 9.77 s. The current women's record is 10.49 s by Florence Griffith Joyner, set in 1998. Men take 44 steps to cover this distance; women take 49–50.

The piece was inspired by trying to combine the beauty of Scriabin's mystic chord, which I had just discovered (chord 1 of the piece) with the beauty of performance of the world's finest athletes. The chords, tempos, and intensities match each footstep of the race and reflect the mindset and physiology of the athlete. The notation is my own, invented for the piece; it takes at least 5 pages of notes to explain all of this in words, yet here in 4 lines, 44 notes is a representation of both a high-performance athlete and a musical wonder, Scriabin's mystical chord.

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