Discovery and Creation:
Opposite Ends of a Continuum of Constraints

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Introduction

Robert Boyle, the great 19th century English chemist, *discovered* the law of gases that bears his name; he did not create it. T. S. Eliot, the great 20th century American poet, *created* a poem called the "The Wasteland"; he most assuredly did not discover it.

Nothing could seem less controversial. And yet, the twin notions of discovery and creation are nonetheless very closely related in our minds. The main difference between them seems to depend on the ineluctable nature of discovery compared to the unique character of the creation. Scientific laws are thought of as being found, discovered, stumbled on, or uncovered, whereas plays, poems, novels, paintings, and symphonies are all thought of as having been created. However, in this essay I hope to show that discovery and creation are, rather counter-intuitively, largely manifestations of the same underlying cognitive mechanisms.

The idea is that scientific laws have an existence independent of humans and become revealed to us when someone — an Einstein, a Newton or a Curie — comes along and discovers them. In the same way that ancient explorers found new and uncharted lands, scientists find new and uncharted laws of nature. It is this notion of prior existence that is largely absent in the notion of creation. It is due to this notion that scientific laws are "out there" to be discovered that we are comfortable with statements like, "If Einstein hadn't discovered Relativity, someone else would have discovered it within a decade." But imagine someone saying: "If Da Vinci hadn't created the 'Mona Lisa' someone else would have within a decade." The former claim seems perfectly reasonable; the latter absurd. Why? Because Special Relativity seems to have an existence of its own, independent of humans. We believe that beings on a planet orbiting Alpha-Centauri could discover it, too — and almost certainly would — if they were intelligent enough. This is why it seems appropriate to talk about Einstein's *discovery* of Special Relativity, but Da Vinci's *creation* of the "Mona Lisa." The painting, unlike the Theory of Special Relativity, is tied to Da Vinci and only to Da Vinci and, as such, we feel that it is unique. In short, it did not exist until it was produced by him. It is not, therefore, something that can be discovered.

And yet, both Da Vinci's Mona Lisa and the Einstein's 1905 paper on the Theory of Special Relativity involved the production by their authors of patterns: in the first case a pattern of paint spots on a piece of canvas, in the second, spots of ink (called "words") on a piece of paper. Why does the word "discovery" apply to one, but not the other?

Central thesis

The central thesis of this paper is that, even though we may think of creation and discovery as being separate phenomena, they are really manifestations of the same underlying mechanism. Whether something is called a creation or a discovery is a function of the number and rigidity of the constraints within which its author is working. The more and tighter the constraints, the more something is perceived of as a discovery. Loosen the constraints and it becomes a creation. I will suggest that there is a continuum of constraints that defines the range of disciplines in which scientists and artists work. This continuum runs from disciplines in which the constraints are absolutely rigid — for example, pure mathematics — to those where there are hardly any at all — for example, modern abstract art. Secondly, I will claim that what we commonly view as creation can be appropriately viewed as the emergent products of many, many little discoveries. So, just as largely unpredictable cognitive activities can arise from the multitudinous interactions of low-level deterministic process (neuron firings), so, too, can many aspects of creations arise from low-level ("local") discoveries regarding forms, rhymes, colors, etc. that work.

In what follows I hope to illustrate these points by examining a number of different examples that will allow us to explore the continuum running from discovery to creation.

Science and Discovery

Mathematics

Mathematics is, by definition, the most constrained of all disciplines. Once one has accepted the axioms on which a particular area of mathematics is based — for example, Euclid's axioms of geometry or Peano's postulates for arithmetic — and the rules with which to manipulate them, one is locked into a system of absolute constraints. There are, to be sure, an infinite number of pathways to explore, but they are all defined by a set of rigid constraints. This set of rigid constraints is what gives us the impression of the inevitability of mathematical theorems. One *discovers* a proof of the impossibility of trisecting an angle with a compass and straightedge because either the theorem exists (even though it hasn't yet been proved) or it does not (in which case, the goal is to discover a proof of the negation of the theorem). One of the reasons that Gödel's Incompleteness Theorem (1931) shook up the foundations of mathematics was because it undermined this ubiquitous belief in the ultimate provability of all mathematical truths.

In spite of his famous theorem, Gödel, like almost all mathematicians and most scientists, believed that mathematical theorems had an existence completely independent of humans. They were "out there" to be found by intelligent beings. I believe that the idea of the independent existence of mathematical theorems is a direct consequence of the nature of the constraints on mathematics. These constraints are perfectly rigid and this rigidity gives rise to the notion of a pre-existing "path" from one mathematical truth to another — one that can be discovered, but is certainly not *created* by us. Mathematical truths are usually perceived as nodes in the deterministic web of all possible theorems radiating outward from the original set of axioms (even though Gödel showed that this view was, in fact, flawed). Consequently, our perception of mathematical truths is that they are determined, pre-existing objects. It is this determinism that gives rise to our belief that their existence is independent of our own. Mathematical truths are, therefore, objects that one can discover, and would ultimately be discovered by any intelligent creatures in the universe. One does not create them, one discovers them.

Physics

Physics is similar to mathematics in terms of the constraints imposed on it. The key difference is that in physics some of its constraints are empirical in nature, rather than purely logical. The laws of physics must adhere to the constraints imposed by empirical observation. The rigidity of the empirical constraints to which any theory in physics must adhere put physical laws in a similar category with the Prime Number Theorem, space-filling curves or Cantor's discovery of various sizes of infinity.

Few would argue with the idea that Newton's discovery of the law of universal gravitation ranks among one of the great intellectual achievements of human history. But if it was "merely" a discovery — with all the ultimate inevitability that we associate with discoveries — why is Newton so lionized? It is clear that had Newton not discovered the law, someone else eventually would have. (In fact, Robert Hooke, a contemporary of Newton's, was very close.)

The reason, I believe, is that, even though we accept the ultimate inevitably of the discovery of the law of universal gravitation, the *difficulty* of finding the path leading to the law is the determining factor. The number of potential paths of discovery emanating from a starting point that was a particular set of laws of motion, was extraordinarily high. To have discovered precisely the path leading to the law of universal gravitation was rightly recognized as a feat of historic proportions, even if the number of potential paths was not so high as to have made it completely impossible for any other human to have achieved it.

In physics, as in mathematics, there is a notion, however poorly defined, of "distance traveled" to discover a new theorem or physical law. The "distance traveled" from the current state of knowledge is a crucial consideration in judging the importance of a particular discovery. The fewer the steps from current knowledge, the lesser the achievement. On the other hand, if a theory makes a considerable number of "logical" steps from the current state of knowledge and is, nonetheless, confirmed by empirical data — this is considered to be a significant advance.

For example, the notion that the path of a light ray would be bent by a massive body was a completely novel prediction of Einstein's General Theory of Relativity. When it was confirmed, Einstein became an international scientific celebrity. However, his faith in the rigid nature of the constraints (in this case, essentially mathematical) of theoretical physics caused him to be unmoved by the news of the confirmation of his theory by Eddington's 1919 solar eclipse expedition. Asked why he was not more excited by the news, he reputedly replied, "But I knew that the theory is correct."

In short, in spite of the inevitable character of his discovery, the feeling was that his was a great discovery because:

i) he had respected the large number of rigid constraints imposed by both theory and empirical data;
ii) he had moved a considerable distance from the current state of the domain;
iii) empirical data had confirmed his theoretical predictions.

One way to view the act of creation within the rigid constraints imposed by mathematics and the hard sciences is as follows. The creative act is *selecting the right path,* from among all the possible paths defined by the constraints. If the path is short, we recognize that it would not be hard for many people to find it. The longer the path, the less obvious it becomes to find, the less inevitable. The less inevitable, the more the term "creation" applies.

For example, if a particular mathematical or physical exploration goes very far beyond the current state of knowledge, we become more comfortable with the notion of *creation*, rather than discovery. One example is particularly striking: At age 16 Evariste Galois discovered a proof of a two-millenium old problem that angles cannot, in general, be trisected with a straightedge and compass. To solve this problem he moved mathematics very far from its state in the 1820's. In fact, his ideas were so far from the dominant paradigm (i.e., currently accepted set of constraints) that we are comfortable with statements like: "In order to solve the problem of the trisection of an angle with a straightedge and compass, Galois *created* an entirely new area of mathematics, today known as Galois Theory."

We will return to the notion of creation within a set of rigid constraints later in this paper.

Chemistry, Biology, Archeology, Paleontology, etc.

From physics we gradually move towards the “soft” sciences. The primary reason that these sciences are called “soft” is because of the nature of the constraints on them. The less rigid the constraints, the “softer” the science and the more the word “discovery” becomes hard to justify.

Consider, for example, clinical psychology, arguably the softest of sciences. Its practitioners do not discover methods of treating patients in the same way that, say, a physicist discovers the principles underlying the transistor. They invent (or *create*) these methods of treatment. This is because of the number and rigidity of the theoretical and empirical constraints is far lower in clinical psychology than in, say, physical chemistry. The number of degrees of freedom in clinical psychology is simply too high for us to feel comfortable with the notion of the independent existence and truth (or falsehood) of propositions in this discipline.

Art and Creation

T.S. Eliot did not discover *The Wasteland*, any more than Shakespeare discovered *Hamlet*, Rodin *The Thinker,* or Manet *Dejeuner Sur l’Herbe*. They *created* these works. In short, these works are intimately associated with their authors. They do not have an author-independent existence as do, for example, atoms or beams of light.

However, the underlying intellectual process is very similar to the one underlying discovery. In both cases, the authors are bound by constraints. The difference is that, in the arts, these constraints are far fewer in number and less rigid in scope than in the sciences. For this reason, from a given starting point one cannot hope to predict the “trajectory” of an artist’s paintbrush or a sculptor’s chisel. Unlike the scientist, there are just too many possibilities to make this possible. The fan-out of possibilities at each decision-point is simply too high.

This, however, would make it seem like creation and discovery are, indeed, very far apart. I hope to show in what follows that certain areas that would seem to fall clearly within the realm of creation can be transformed into discoveries by tightening the constraints applied to them. Conversely, areas that seem to fall clearly within the purview of discovery can, by relaxing the constraints, be moved towards creation.

When creation becomes discovery

Let us start by considering poetry in its most unconstrained form, free verse. It is inconceivable that if you said to two different people, “Write a poem about love” that the two individuals would write a word-for-word identical poem. Each of them would *create* a different poem.

Let us start increasing the constraints in order to push creation towards discovery.

We begin by tightening the constraints on the meter and rhyme scheme: “Write a poem about love that is four lines long, each line has four words of less than five letters each, and has an ABABA rhyme scheme.” Now, the two poems would be much closer, although they would still have none of the inevitability of a mathematical theorem or a law in physics.

We add: “And the first letters of the words in the first and the third line must spell G-A-R-Y, in the second and fourth line: L-I-S-A .”

And then: “And the letter “e” cannot appear anywhere in the poem.”

And so on. At some point, the two authors will begin to converge on very similar poems. Each additional constraint forces the authors to narrow their choices of possible words and the writing of the poem becomes more and more like solving a puzzle. For example, since the love poem they are supposed to write cannot use words like “love,” “like,” “sex,” etc.

because all of these words contain an “e”, there is a high probability that they will both *discover* the word “amour.” Or perhaps they will discover that the only word that begins with a “Y” and that satisfies all other the constraints is “YOU”. Under these circumstances, one can imagine one of the poets finding — *finding* — an extremely original, elegant solution that respects all the constraints that will cause the other author, upon seeing it, to say, “I wish I’d discovered that!”

The point is that the imposition of constraints gradually transforms what we think of as creation into a process of discovery.

Edgar Allan Poe’s *The Raven*: a case study

Some writers do, in fact, feel that the constraints involved in writing poetry result in its being essentially the same type of endeavor as doing physics. In an essay entitled “The Philosophy of Composition” Edgar Allan Poe (1846) discusses in detail how he was able to “discover” (to use the language of the present paper) the words and structure of his most famous poem, *The Raven*. He describes the composing of the poem as an inevitable mathematical-logical progression towards the wording of each stanza as it actually appeared in print, once he had made a certain number of decisions (the “postulates” of his poem, as it were). He wrote: “It is my design to render it manifest that no one point in [*The Raven*’s] composition is referrible either to accident or intuition — that the work proceeded, step by step, to its completion with *the precision and rigid consequences of a mathematical problem* [my italics].” He then goes on to “demonstrate” the mathematical manner in which he arrived at each word, each rhyme of his poem. In other words, Poe considered the writing of *The Raven* to be a mathematical process of discovery rather than creation. (See Hofstadter (1998) for a particularly interesting discussion of Poe’s essay as it relates to creativity.)

Creation as emergent discovery

The fact that *The Raven*, as a whole, was more like an inevitable, mathematical discovery is, of course, vastly overstated. What would have been more reasonable would have been to claim that *locally* (i.e., the choice of particular words at particular points in the poem) *and because of the high number of constraints* (i.e., necessities of rhyme, meter, and content) *imposed at that particular point*, certain choices he made had a degree of inevitability that better lent themselves to the concept of discovery than creation.

On this basis, one is led to the idea of creation as the emergent product of myriad micro-discoveries. At first blush, this would seem to imply that creation must therefore have the inevitable quality that would seem to be the hallmark of discovery. But upon closer reflection, we can see that this is not the case. Recent work in chaos theory (Schuster, 1984, Lorentz, 1993) has laid to rest the Laplacian notion that low-level determinism would produce a universe where all high-level actions could be predicted, if only our observation and computing devices were better. While we, of course, have some short-term ability to predict high level patterns, the computational complexity of long-term prediction has now been shown to be beyond the reach of any conceivable computing device. In short, there is no hope of accurate long-term high-level prediction of the outcome of myriad interacting low-level events, however deterministic they may be.. The same applies to low-level discoveries that ultimately lead to high-level creation. The latter may, indeed, emerge from the former, but there is no sense in which we can predict it.

Now let’s translate this into the concrete terms of writing a poem. Consider a particular low-level juncture in a poem, instead of considering the poem as a whole. The poet needs a particular word to complete a verse. What has preceded that particular word has engendered a host of constraints involving its number of syllables, its pronunciation, its content, its connotation, its final syllable, etc. All of these constraints add up to a quasi-inevitable "choice" for the word. In other words, if, immediately after choosing the felicitous word, the original poet covered it up and asked a poet friend what word he had picked, what are the chances that the friend would be able to discover the same word that the original poet had used? The answer is: high, but not perfect. And it is this "not perfect" that, when extended to an entire poem, makes the creation of the poem *as a whole* unique and not inevitable.

Discoveries, too, are emergent products of many micro-discoveries, but the difference with creations is that for discoveries, the fan-out at each choice point is more constrained. And this is what gives them a greater degree of inevitability at the global level. On the other hand, even in a highly rigid domain such as mathematics, when a particular individual goes far enough beyond the realm of the currently accepted framework (see the above example of Galois), so far that the notion of inevitability is basically lost, then we are happy to call the result a creation.

The different quests of Pierre Menard and "Paul Menard"

Now, let us consider a famous creation by Luis Borgès, Pierre Menard, who embodies the same attitude that Poe expresses in his essay. Menard attempts to study the full set of constraints under which Cervantes lived — *everything* about 16th century life in La Mancha, *everything* involving Cervantes' life, *everything* about all the people he interacted with throughout his entire life, etc., in short, every last detail of Cervantes' existence and surroundings — so completely and in such exquisite detail that Cervantes' masterpiece, *Don Quixote*, its every word, period and comma, would flow from his pen, without his ever having read a single word of the original. Borges' short story can be read as an inimitable parody on the deconstructionist notion that the constraints on an author, like those on mathematicians or physicists, are rigid, well-defined and sufficiently numerous that the author is no more necessary to the novel than Einstein was to the Theory of Special Relativity.

Borges' story is famous because it takes the deconstructionist notion of the unimportance of the author (and, thereby, the importance of constraints) to its logical (and absurd) conclusion. One reason the story is so appealing is that, while we recognize that such a perfect recreation of *Don Quixote* would be impossible, we recognize that the underlying idea makes *some* sense because if, as in our imaginary love poem, we could reproduce all of the same constraints that Cervantes had, we can imagine — just barely — that Pierre Menard's quest might be possible. (See Hofstadter, 1998, for a discussion of Pierre Menard's quest and its relation to creativity.)

Now, by way of contrast, imagine that Pierre Menard, had had a brother, a mathematician named Paul. Upon learning about the existence of non-Euclidean geometry and its discoverer, Nicolay Lobatchevsky, he says, "I, too, am going to discover Lobatchevskian geometry. However, I will not read anything whatsoever about it per se. Rather, I am going to study in the most minute possible detail everything that Lobatchevsky ever knew before he made his discovery, everything about Lobatchevsky himself, everything about his contacts and conversations with other mathematicians, everything about the ideas that were in the air at the University of Kazan in the late 1820's, etc. And, if I am thorough enough, I, too, will be able to discover Lobatchevskian geometry." Because of the perceived character of logical inevitability of mathematics, Paul's quest seems somehow more reasonable than Pierre's. At the very least, we believe that while both quests would fail, the one without any hope whatsoever is Pierre's

If we replaced "Lobatchevskian geometry" with "The Theory of Special Relativity," we would still be able to make a reasonable case for its potential discovery by someone else. Once again, the reason is the far higher number and rigidity of the constraints placed on discoveries in physics than on artistic creations. However, as we move farther along the constraint-continuum to, say, Freudian psychology, we can no longer imagine discovering the

Freudian theory of child development, anymore than we can imagine a letter-perfect reproduction of *Don Quixote* by someone other than Cervantes. Freudian psychology does not have the inevitability, and thus the discoverable existence that we ascribe to, say, the Theory of Relativity. The development of Freudian psychology was very much the work of a single individual and is not circumscribed by a vast and rigid web of deeply intertwined logical and empirical constraints as is the Theory of Relativity or, to an even greater extent, Prime Number Theory in mathematics.

When discovery becomes creation

Another clear illustration of multitudinous "micro-discoveries" engendering creation can be seen in the game of chess.

Almost all games have rigid sets of rules (i.e., constraints) that players must obey, but often the deterministic aspect of the game is intentionally removed by introducing such devices such as dice or playing cards, etc. On the other hand, there is no introduction of chance in chess-playing. If we could see far enough into the future and calculate quickly enough, the outcome of any chess game would never be in doubt. Yet, despite its deterministic nature, chess-playing seems to fall into the category of creation rather than discovery. The constraints of chess are perfectly rigid, to be sure, but are also relatively few in number: they describe the legal moves of each piece and how captures may occur. The game is such that, at least for a beginner, there is no overall sense of inevitability. The fan-out of potentials moves, counter-moves, counter-counter-moves, and so on, is so high that the sense of "discovering" a powerful sequence of moves does not seem to apply. We say the player has "developed" or "established" (i.e., created) a powerful position.

But notice a particularly striking shift in our perception during the end-game. The end-game is characterized by the small number of pieces remaining on the board. This means that the fan-out of possible moves and counter-moves becomes far more tightly constrained: Once again, we return to the language of discovery, and not creation. In fact, chess journals recently reported that a particular end-game strategy had been *discovered* that produced a victory for one of the players in a particular end-game configuration that had long been thought to necessarily conclude in a draw.

In many ways, the mechanization of creativity (see, for example, Hofstadter, 1985) has long been one of the explicit goals of artificial intelligence. The belief in the possibility of mechanizing creativity is grounded in the notion of low-level "discoveries" (i.e., mechanical, inevitable, deterministic, and, as a consequence, *programmable* actions) out of which will come high-level, unpredictable creations.

Creativity within discovery

In mathematics, as in chess, we can talk about creative solutions to problems. This is another case of "creativity" within "discovery." While it is true that the number and rigidity of constraints in mathematics and physics (and the "hard sciences," in general) confer on them an aura of ultimate inevitability, there is still an enormous room to maneuver within the dictates of these constraints. So, for example, one might imagine solving the Four Color Problem (i.e., no more than four different colors are necessary to color any map) in a variety of ways. It was actually first proved in 1976 at the University of Illinois by Kenneth Appel and Wolfgang Haken using a "brute-force" technique involving the computerized examination of a catalog of 1,936 different basic map configurations and requiring thousands of hours of computing time. To be sure, the proof of the theorem respected all of the constraints of any proof in mathematics, but was it considered elegant? Certainly not; Appel and Haken's proof was brute force at its best. Had someone been able to find a completely unexpected, but perfectly accurate three-page proof using a technique from, say, knot theory, the new proof would be hailed as highly "creative." But why? Doesn't this second demonstration have the same logical status as the first? After all, both lead with mathematical inevitability to an identical result —namely, the proof of the Four Color Theorem. Yes, but there is a difference.

While it is true that both proofs are, perhaps, "inevitable," in the sense that someone else was bound to have come along, sooner or later, and discovered one or the other of them, the latter has a deeply unanticipated nature. In other words, among all the possible proof-paths that conclude at the Four Color Theorem, the short, elegant one seems to us to be far less inevitable than the brute-force proof. A trudging proof leading to the Four Color Theorem has a certain inevitably — and thus discoverability — to it, but the elegant, unanticipated proof has more the feeling of creation. And for this reason we tend to applaud this elegant solution as creation, and not "merely" as discovery.

Constraints define different types of discovery

A friend of mine recently became enthralled in Euclidean plane geometry. His interest in the subject grew into a passion and he discovered a number of new theorems. To his disappointment, however, these results were largely ignored by the larger mathematical community. The question is why are results in Euclidean plane geometry considered to be less interesting, say, than new results in von Neumann algebras?

An analogy might shed some light on this conundrum. Compare the progressive exploration of the west coast of Africa in the 15^{th} Century with Columbus' voyage across the Atlantic. Both types of exploration did, indeed, chart previously uncharted lands, but the latter was a much more significant discovery. Why? I believe the answer lies in the fact that in the first case there is a sense of inevitability not present in the latter. African coastal exploration was constrained to the point of quasi-inevitability. Explorations that have explored 1000 miles of the coast, can be reasonably expected to continue for an additional 100 miles along the same coast. On the other hand, the outcome of sailing forth into the Atlantic was far less certain. The outcome was far less predictable (because less constrained), and hence the achievement considered to be greater.

The same is true with scientific exploration. "Exploring" Euclidean plane geometry is much like exploring the African coast in the 15^{th} century. There is a perception of inevitability because the subject has been so thoroughly explored in the past. One is working within a vast and extremely constraining web of former research. Discoveries in plane geometry are like discovering yet another peninsula along the African coast: It is, indeed, a discovery, but is not considered to be particularly interesting because of its perceived inevitability.

Different nature of constraints in science and art

There is one essential difference between the constraints of scientific discovery and those of artistic creation. The constraints of discovery are, as a rule, *external* constraints, whereas those of artistic creation are, in general, *internal*.

In other words, a physicist is not allowed to alter constraints such as the speed of light, Planck's constant, the gravitational constant, etc. These are imposed, in some sense, externally. A theory of physics or chemistry or biology *must* accommodate empirical observation, otherwise it is rejected as false. There is no such notion of empirical verification of theory, of truth or falsehood where creation is involved. The constraints are largely internally — which often means *culturally* — imposed. In fact, with this in mind, the French poet, Paul Valéry (1950), once defined poetry as freedom within arbitrary constraints. In other words, he emphasized the necessity of constraints within which art must work. There is no "genre-less" art.

Constraints and "sameness" in art and science

It has also been pointed out to me (M. Weaver, personal communication) that another way of looking at this separation between discovery (in the sciences) and creation (in the arts) is through the lens of "sameness." For example, we believe that Charles Darwin and Alfred Russell Wallace independently "discovered" the *same* theory of natural selection, even if the respective papers that they wrote on the subject were not (obviously) word-for-word identical, or even close to it. We can say the same about Newton and Leibnitz' discovery of the calculus. Their description of the tool they discovered, today called the infinitesimal calculus, was very different, but the underlying idea was, in both cases, identical. Thus we credit both men with the discovery of the calculus. And there are many other examples of this type: independent discoveries of mathematical or scientific ideas. In mathematics, the most constrained discipline of all, independent discoveries of theorems occur all the time and this bespeaks of the inevitable nature of mathematics. As we move from the most to the least constrained domains of science, the number of independent identical discoveries falls accordingly.

And our notion of discovery applies, in fact, to any process in which the notion of inevitability is paramount. It is believed that the eye evolved independently between 40 and 60 different times (Ridley, 1998; Salvini-Plawen & Meyer, 1977). Indeed, Nilsson & Pelger (1994) describe the process as if it had a certain "mathematical" inevitability about it. In other words, Nature is solving a mathematical problem. They write, "...if the objective is limited to finding the number of generations required for the evolution of an eye's optical geometry, then the problem becomes solvable." They conclude that "363,992 generations would be sufficient for a lens eye to evolve by natural selection." If Nilsson & Pelger's model is accurate, the number and rigidity of the constraints affecting eye development is such that the evolution of the eye falls squarely within the realm of discovery, discovery by evolution. Starting from "a flat patch of light-sensitive cells sandwiched between a transparent protective layer and a layer of dark pigment" they produce a very plausible sequence of environmentally constrained events that would lead to "the camera-type eyes of aquatic animals."

Now, consider art. Only forgery can lead to the reproduction of an already existing work. However, there is a level at which "discovery" can apply to literature or mythology or art. The myth of the virgin birth, the myth of creation, or of the inauspiciousness of twins, etc. have been "discovered" independently by numerous groups of people. And, in this case, one can reasonably argue that the environments that gave rise to these myths — especially, the common forces of survival and death — were sufficiently constrained to produce these identical high-level concepts.

Fractal art

Fractal art provides an illustration of constraint-driven art that is on the boundary between discovery and creation.

Let us begin by supposing that a painter in the 1950's had conceived of the key notion of fractal art (i.e., self-similarity at all levels of description) and had begun to make paintings based on that notion. Had he then produced a number of paintings based on this idea, his paintings would certainly have been hailed as creative works of art — creation, in its most generally accepted sense.

Now, let us move the clock ahead thirty years. We now know exactly how to generate fractal art by computer by modifying a number of parameters in an extremely simple set of equations. The art, however beautiful, becomes the inevitable product of a set of constraints. Next to two beautiful fractal pictures (Peitgen et al., 1992), for example, we are given the precise mathematical description of the origin of each picture. We are told that the first is a "Julia set of the quadratic family for c = -11+0.67i.", whereas for the second image we are told that we are looking at a "Julia set of the quadratic family x^2+c. For c = –0.39054–0.58679i a Siegel disk is obtained." In this context, it makes perfect sense to say, for example, "She discovered a beautiful variation on the Siegel disk," rather than, "She created a beautiful variation on the Siegel disk."

On the other hand, the fact that the small parameter changes produce enormously different results attenuates the notion of inevitability associated with discovery. The loss of a feeling of inevitability brings us back to the notion of creation. Because of the non-interchangeability of authorship of creations, the concept of authorship — and its legal manifestation: copyright — arguably applies. And, indeed, many of the fractal images "discovered" by Benoit Mandelbrot and his colleagues are now copyrighted. Thus it seems that fractal art is poised in a blurry area on the continuum from discovery to creation.

Other blurry areas between creation and discovery

A number of other areas fall between the discoverability that characterizes mathematics and the creation that characterizes art. For example, in the area of lawmaking, conservatives want judges to "discover" the law. In other words, they want very tight constraints on judges so that little or no discretion remains in the decisions they produce. In this view, judges discover new interpretations of the law because there are enough constraints on them to do so. Their opponents think that the constraints on judges *cannot* realistically be tightened, even if tightening them would be politically and legally desirable. Hence they argue that judicial *invention* of law is unavoidable. (See Suber, 1998, for a discussion.)

Another area that arguably runs the gamut from pure discovery to pure creation is that of inventions. It is reasonable to see some as the product of discovery given constraints on the human condition (e.g., clothing, fire), others do not have this inevitable feel to them at all (eg., lipstick dispensers, forks), and most fall somewhere in between.

Loosening or modifying constraints

Thomas Kuhn (1962) made a well-known distinction between "normal" science and "revolutionary" science. The key to this distinction in Kuhn's view was whether or not a "paradigm shift" was involved. Thus, Copernicus' contribution constitutes "revolutionary" science, whereas recording changes in the pollution levels of American rivers is "normal" science. His central claim was that there was a fundamental difference between the two types of science.

Whether or not one accepts Kuhn's central claim, I believe there is another way of framing this apparent difference and that is by examining Kuhn's claim in terms of the notion of constraints and constraint-modification developed above.

The more scientists work within all of the established constraints — the closer they are to "normal" science; the more constraint-bending that is required, the closer they are to "revolutionary" science.

Let us start by considering what we might call "verificationist" science. These are scientists who are essentially working within the framework of all of the constraints that have been previously established for their particular area. The explicit goal of their work is to verify predictions derived from a set of constraints, rather than to modify the set constraints. For example, if a particular model predicts that there will be an ozone gap over the South Pole in the Antarctic summer, the scientists who fly planes into the ozone layer above the South Pole to verify (or disprove) this prediction are doing verificationist science. There is no attempt at modification of any of the constraints of the model that we are testing. This type of science has the most inevitable feel to it. Researchers involved in verification science are generally considered more interchangeable than others for whom constraint-bending plays a role in their work.

One moves away from verificationist science in small, incremental steps. Many scientists slightly modify minor constraints (i.e., parameter modifications) and explore the consequences of these changes. As the fan-out of possible outcomes increases, the sense of inevitability decreases. The author of this kind of research has many choices: Which parameters should I modify? By how much? What should I add to the existing model? This decreases the feeling of interchangeability of the scientist that we encountered in verificationist science. The "creation" was in the *choice* of the parameters to change, the new values to try, the additions to be made. The closer one is to pure verificationist science, the more local are the constraints that are modified. As the constraints that are proposed for modification become more "global" — i.e., apply to more than just the specific question under consideration — the more the nature of the science being done is "revolutionary." In short, not all constraints are of the same importance. The importance of constraints depends on their generality. The more "revolutionary" a scientific undertaking is, the more general are the constraints that it advocates modifying. "Revolutionary" science is considered to be "greater" science than verificationist science (i.e., "normal" science in Kuhnian terms) because of the lesser degree to which it is considered to be able to be discovered. Revolutionary science, in a word, is less inevitable than normal science.

Constraints and situated science

Science must, of course, be situated within a network of constraints. This is largely what distinguishes "crackpot science" from real science — specifically, the former does not fit into the vast web of constraints that are the product of centuries of past research. On the other hand, "revolutionary" science modifies major, accepted constraints that are part of the scientific canon. In the latter case, the work still fits tightly within the web of *most* prior constraints, whereas crackpots are uninterested in fitting their novel ideas into this tight web of constraints. In any real advance in science, revolutionary or otherwise, whenever constraints are violated, they are violated for precisely defined reasons — and, crucially, these reasons fall within the overarching constraints of the discipline. This leads to testable predictions that may show that the proposed constraint-modifications are wrong.

Constraints and situated art

An almost identical logic applies to art, the major difference being the lack of an empirical basis for demonstrating the truth or falsity of a modified constraint. The number of possibilities for constraint-modification is so high, however, that we must abandon any notion of discovery. The correspondence of what is called empirical verification in science is replaced by "general appreciation" in art. As in science, constraint-modification in art is a gradual, incremental process. Thus, for example, impressionism, to say nothing of the 20th century art of, say, Dubuffet, Miro, or Pollock, could not possibly have grown out of the stylized art of the Middle Ages. The "distance" between the two art forms, as measured in the number of major constraints modified, is simply too high.

Conclusion

Without constraints, there is neither science nor art, neither discovery nor creation. This is obvious for science, less so, perhaps, for art or literature. A dozen eggs tossed on the sidewalk is not art; a collection of randomly chosen words on a page is not literature. Art, like science, works within a system of constraints that are incrementally modified with time.

Further, many of the aspects of creations can be viewed as the emergent result of many, many small quasi-inevitable discoveries.

It is the notion of constraints that distinguishes discovery from creation. A large and encompassing web of rigid constraints gives rise to discoveries. Loosen the constraints enough, thereby removing the sense of inevitability, and we are in the realm of creation. The unifying factor is the idea of a continuum of constraints, at opposite ends of which lie discovery and creation.

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