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The Stitching and the Unstitching: What Can Behavior Analysis Have to Say About Creativity?

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Traditional critics of behaviorism and behavior analysis have emphasized that these approaches cannot deal with creative achievements in the arts or sciences, or even in ordinary speech. This essay explores several lines of research and conceptual issues from different sources in an effort to refute this claim. The emphasis is on scientific and mathematical creativity. Some of the topics considered include the role of special practice and manipulation, conditions for development of automaticity, the interplay of contingency-controlled and rule-governed behavior, modeling, abstraction, intuition, the blending of response units, and emergent behavior. Some limitations of a behavioral account are also considered.

Key words: creativity, problem solving, automaticity, genius

Until relatively recently, the science of behavior has given little attention to the behavior of scientists. Science as a practice has been primarily the province of philosophers, historians, and, of late, sociologists. Skinner (1957) may be credited with perhaps the first attempt to treat scientific practice in the context of a larger theory of verbal behavior. One essential principle of Skinner's approach is that such behavior is operant behavior, and thus it may be shaped and manipulated to yield new verbal behavior. Although the practice of science, including mathematics, may ultimately have nonverbal consequences, I am going to focus almost exclusively on science as creative verbal behavior. What follows is a portion of a halting and mingled first effort to explore and summarize possible contributions of behavior analysis to understanding major examples of scientific, including mathematical, creativity.

Skinner begins *About Behaviorism* (1974) with a list of what he deems misconceptions about behaviorism. Number six of that list states, "It [behaviorism] cannot explain creative achievements—in art, for example, or in music, literature, science, or mathematics" (p. 4). Skinner, of course, subsequently addresses this criticism in ways I'll touch upon later. As a prelude to a general behavioral approach to creativity, I think it is useful to consider first the sources of the criticism and then attempt to specify the dimensions of creativity in a behaviorally useful way.

Creativity has been the subject of an enormous number of books and other sources. Typing in the term *creativity* on Amazon.com yields more than 1,200 titles! I want to state at the outset that a primary inspiration for my approach here comes from Weisberg's two books on creativity (*Creativity: Genius and Other Myths,* 1987, and the more elaborated follow-up, *Creativity: Beyond the Myth of Genius,* 1993) and his recent article in Sternberg's *Handbook of Creativity* (1999). As apparently a dedicated cognitive psychologist, Weisberg might consider my inspiration as a kind of apostasy. So be it; he is far more astutely behavioral than most of the colleagues he criticizes. Other useful sources include Simonton's excellent *Origins of Genius*

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(1999) and Eysenck's *Genius* (1995). These three authors are in mutual disagreement on many issues, but collectively and selectively, their perspectives resonate well with a behavior-analytic view. In particular, their approaches are fundamentally empirical; they seek, cite, and critically evaluate historical, experimental, and psychometric evidence for their assertions. They all in one way or another emphasize the roles of variation and selection in the generation of creative behavior. Although with each investigator the primary focus is upon "genius," all their approaches admit some continuity between ordinary problem solving and outstanding achievement.

Another vital source for me is the work of a number of behavior analysts that bears directly or indirectly on the topic of creativity. To name but a few in addition to Skinner, and here without citing specifics, I include Andronis, Binder, Catania, Barnes-Holmes, Epstein, Hayes, Layng, Lindsley, Mechner, Neuringer, and Sidman. My general approach to the topic prevents any but the most superficial mention of the contributions of these creative researchers.

A final major source, which actually initiated this interest, is my own very long history of studying with fascination and delight the lives of the great physicists and mathematicians of modern history. Their biographies and autobiographies, when carefully presented, generally affirm major elements of Weisberg's, Simonton's, and Eysenck's perspectives, and, to my thinking, a behavior-analytic approach, as I will try to illustrate. I wish also to emphasize in this prelude that, although I believe behavior analysis has a major place in the study of creativity, there remain very significant issues not directly addressed by any empirical approach, behavioral or otherwise.

The criticism that a behavioral perspective is not useful in understanding creativity begins to tell us something not only about how the critic views behaviorism, but, more important, about how creativity itself is viewed. Perhaps no other significant human activity is looked upon with such awe and mystery. Those who have been particularly successful creators are deemed "geniuses," and are thought to be literally a different ilk of human being, possessed with divine inspiration and utterly unique powers. Plays like *Amadeus* and numerous Hollywood biographies of great artists, musicians, scientists, writers, and the like, portray and reinforce this picture of very special individuals who spew forth astonishing works in plenitude as if by magic. Wondrous works emerge in mature perfection from the realms of intuition, unconscious incubation, and lightning flashes of insight illuminating the depths of human understanding and possibility. If all this were true, not only would behavior analysis be helpless, but so would any other scientific approach as well. Yet, there is something in this fantastic and romantic picture to give us pause.

Why the emphasis on genius? Simply because whatever the particular traits the term implies, for many, people with notable creative products *are* mysterious, and their accomplishments do appear as magical. Even those who by some criteria might be labeled as geniuses themselves see certain others as magicians. Here is a famous observation by Marc Kac, who was a very eminent mathematician:

> In science as well as other fields of human endeavor there are two kinds of genius: the "ordinary" and the "magicians." An ordinary genius is a fellow that you and I would be just as good as, if we were only many times better. There is no mystery as to how his mind works. Once we understand what he has done, we feel certain that we, too, could have done it. It is different with the magicians. They are, to use mathematical jargon, in the orthogonal component of where we are and the working of their minds is for all intents and purposes incomprehensible. Even after we understand what they have done, the process by which the have done it is completely dark. (1987, p. xxv)

Kac had in mind people like the mathematician Ramanujan and the physicists Einstein and Feynman, all of whom I will briefly discuss later. So, not only is the term *genius* seen to refer to unique individuals, but also among geniuses themselves there are further divisions of uniqueness. The issue for a behavior analyst or anyone else interested in understanding human performance scientifically is whether we are dealing with a different "species" of creature; or, alternatively, as I think most of my readers probably believe, remarkable accomplishments, even by the "magicians," can be understood to some degree through application of relatively few principles that apply to all of us. However, we should in no way believe that this is an easy task.

Creativity research has been around since the earliest developments in scientific psychology. Major movements and fields such as psychoanalysis, Gestalt psychology, individual differences, psychometric assessment, and modern cognitive science have taken on creativity as a major challenge. Moreover, terms or concepts like *insight, illumination, incubation, unconscious processes, intuition,* and *genius* have been and continue to be woven into the fabric of analyses. These terms address something, despite our possible skepticism about them. Indeed, the field of creativity engenders a unique blend of skepticism and fascination.

Behavior analysis has pursued its own way in this domain, largely ignored or even ostracized from mainstream theory and research. The reasons for this are fairly simple. First, many outside the field see behaviorism and applications of behavior analysis as being totally unable to deal with *novelty.* For example, this view dominated Chomsky's (1959) critique of Skinner's *Verbal Behavior* (1957). It is a perspective also expressed in another criticism listed by Skinner in *About Behaviorism* (1974): "It [behaviorism] formulates behavior simply as a set of responses to stimuli, thus representing a person as an automaton, robot, puppet, or machine" (p. 4). If one really believed this, a person, or any other organism for that matter, would be, at best, a displayer of Pavlovian reflexes, and at its lowliest, a passive, sessile creature wafted about by the vicissitudes of nature. However one might describe it, this is certainly not a being that could manipulate the environment, create agriculture, engineering, art, literature, music, science, or, to be sure, even a novel sentence. What is reflected here, of course, is a profound ignorance and misunderstanding of the science of behavior analysis. This is not the place to explore the sources of this situation, but I will say we behaviorists ourselves bear a significant responsibility, for example, by not exploiting the research done by those in other fields and not publishing our work in the proper places. At any rate, in contrast to the passive, old S-R character attributed to humans by modern critics of behaviorism, one might recall the first sentence in *Verbal Behavior*: "Men act upon the world to change it and, in turn, are changed by it" (p. 1). This sets the tone for what follows.

WEISBERG'S APPROACH

From Weisberg's perspective, past and prevailing views of creativity and genius are saturated with enduring *myths* that have little empirical or historical support. Favored notions such as unconscious processes, incubation, special insights and intuitions, divergent or lateral thinking, set breaking, and so on, are largely abandoned primarily for lack of creditable empirical evidence. For Weisberg, creativity is essentially *ordinary problem solving.* As such, the patina of the unique and the mysterious is removed to reveal a more mundane but still very complex behavior. Thus, continuity is established between, on the one hand, the behaviors of deciding which route to take from New Orleans to Boston or what to prepare for a Saturday dinner for four; and, on the other hand, composing *Tristan und Isolde* or proving Fermat's Last Theorem. Placing creative behavior into the bosom of problem solving makes contact with a vast literature largely contributed by cognitive psychologists in the last three decades or so, but it does not by any means automatically exclude any of the notions previously referred to such as insight, intuition, and so on. His views on many of the conventional and putative dimensions of creativity are not shared by, for example, Eysenck and Simonton, among others. This is not the place to bring out all these potential differences, however important. Moreover, there are some significant variances between some of his views and a behavior-analytic perspective, although I believe them to be minor relative to his general approach. As I will attempt to point out, the creativity-as-problem-solving stance, no matter how controversial, is particularly suited to a behavior-analytic approach. As I will shortly outline, work from several quarters of behavior analysis, basic and applied, bears on successful problem solving and provides some insight into the mysteries of creation.

Two basic questions will serve as a framework for my discussion. First, where do those novel behaviors deemed creative come from? Second, how might we account for individual differences in creative behavior? A third and equally important question is why some works are more valued or influential than others. This latter question is more than worthy of a paper on its own and will not be discussed here.

BEHAVIORAL VARIATION AND SKILL ACQUISITION

A major challenge to anyone attempting to wrestle with *creativity,* never mind *genius,* is to define such terms adequate to an analysis. As expected, well-meaning and indeed useful treatments differ considerably in characterizing just what it means to display creativity and beyond to performances recognized as genius. Weisberg, in emphasizing problem solving, cuts through a number of difficulties. He emphasizes two elements: novelty and goal directedness. This is in accordance with a view of problem solving as an activity of manipulating the environment, including verbal material to achieve some particular effect. I do not wish at this point to explore further various troublesome aspects of his characterization, but rather use it here as a frame of reference.

Behavioral variation is the *Anlage* from which new classes of operant behaviors emerge through *response differentiation.* Thus novelty is inextricably embedded in the defining property of operant behavior; namely, that behavior is controlled or selected by its consequences. Skinner (1938) viewed response differentiation as a dynamic interplay among reinforcement, punishment, extinction, and induction or response generalization. Reinforcement of a response class increases the probability of that class. Responses of a similar form will occur through induction, including responses that fall outside the reinforced class. Extinction can operate to decrease the probability of that class, and again through induction to similar responses. Because the effects of reinforcement and extinction are direct and those of induction are indirect, the former effects are considered more powerful, with the result that the reinforced response class is differentiated from the nonreinforced. Also, as Skinner notes, "Since direct strengthening is greater than indirect, the most frequently occurring form automatically strengthens itself preferentially" (1938, p. 309).

Punishment and negative reinforcement can also play roles in the differentiation process. Thus, behaviors that are difficult, awkward, or effortful, as well as those that differentially result in extended intermittences or delays of consequences, will tend to be selected out. At any rate, very fine-grained repertoires may be shaped through exposure to precise and extended applications of behavior–consequence relations, or contingencies, as we prefer to call them.

To develop extreme response values, or novel and complex performances, variability in emitted behavior can be engendered by withholding reinforcement either through controlled intermittences or extinction. The occurrence of new or more extreme values can then be differentially selected. By repeating this procedure, completely new behaviors never seen in the "natural" repertoires of organisms can be produced. Indeed, it is difficult to imagine how such novel behaviors could be produced by any other means. Even if provided motorcycles in the forest, bears would not ride them, as they are seen to do—as if by magic—in a Russian circus. We all know about the "creative" porpoise trained by Pryor, Haag, and O'Reilly (1969). In this demonstration, reinforcement depended on the porpoise emitting behaviors not previously emitted; in other words, only novel behaviors were reinforced. The porpoise thereby came to exhibit remarkably varied and complex behaviors.

Behavioral variation has also been selected in humans through similar procedures. Neuringer and his colleagues (e.g., 1986) have published a large number of studies showing that subjects can come to emit random numbers through differential reinforcement via feedback from statistical tests of randomness. Again, it is difficult to imagine how this might be accomplished by any other means. Certainly, simple verbal instruction would be ineffective. These kinds of studies provide compelling evidence for behavioral variation as a response class. Of course, variation is but the foundation for creativity, there must also be selection. I will have more to say on this below.

In addition to response differentiation, skill development usually depends heavily on stimulus control processes. Certainly problem-solving skills do. Stimuli, including perhaps complex contextual factors that prevail during response differentiation, come to control subsequent performance through the same mechanisms of selection as response differentiation itself. In its simplest form, this dynamic stimulus–response–consequence interrelation is called a three-term contingency. Of particular importance to problem solving are the processes of stimulus discrimination and its inverse, generalization. These mechanisms determine how behavior will change under conditions of alterations in prevailing stimulus or contextual conditions, including those produced by behavior itself.

As all here know, stimulus control, especially in verbal humans, can achieve extraordinary complexity. The development of verbal behavior itself no doubt depends, at least in part, on the kinds of contingencies I have already outlined. Three major classes of complex stimulus control should be mentioned. The first involves present control by previously imposed contingencies as demonstrated, for example, through recall, recognition, and priming effects, or, in common expression, *memory.* This is a gigantic topic not possible to elaborate upon here except to emphasize the role of history in controlling what classes of behaviors comprise a given repertoire as well as their variability, and the conditions under which these behaviors are likely to be emitted. The second class is *conceptual* or *abstractive.* Through special histories of differential reinforcement, behavior may be brought under control of certain common properties of stimuli. These properties may be extremely subtle, if not fundamentally ineffable. The third class of complex stimulus control is *relational.* This is demonstrated by an enormous range of behaviors, the most interesting of which clearly depend on a verbal history. Symbolic control, equivalence, negation, oddity, ordering, classification, logical implication, and so on, do not begin to enumerate the possibilities of relational control. Also, as yet we do not understand the role of relational control processes in the development of verbal behavior itself. Some kind of boot strapping is very likely, involving

n-term contingencies where n greatly exceeds the well-known three.

These forms of complex stimulus control are not independent of each other. In successful problem solving of any significance, we see blends, interactions, and emergent features involving all of these. Moreover, all are manifestations of an elaborate nexus of shifting conditional probabilities involving symmetric, antisymmetric, and asymmetric relations or associations among stimuli, behaviors, and consequences. This rich ecology of experience is essential to creativity.

Stimulus and response differentiation via selective contingencies place special emphasis on continuity of behavioral change leading to novelty. As Weisberg discusses in detail, great creative accomplishments in all fields depend essentially on antecedents from the work of others as well as from earlier work of the creator. The Wright brothers' airplane, for example, emerged from a complex history including earlier work by Langley and Chanute on wing design and control systems. The change in airplane design over the last century is another illustration of continuity. We could trace a path from Kitty Hawk to Cape Canaveral in terms of differential selection of design in all aspects of flight systems.

In conformity with the previous discussion of complex stimulus control, Weisberg emphasizes two related processes for the generation of novelty; namely, associative links and analogical transfer, both from one's own work and that of others. Although these two concepts are basically akin to our notions of stimulus control and response differentiation, we see how these may be put into good order and extended to conceptual and relational control, basic elements of analogical thinking.

Science, as we all know, abounds with metaphors and models, which, in Mach's terms, are the scaffolding for erecting theories. Faraday's lines of force, Maxwell's hydromechanical aether, and Bohr's planetary atom are major exemplars. The generation and selection of appropriate models is one of the great skills of effective scientific practice. Selecting, including problem finding, as with other operant classes, emerges from a special history that itself needs explication. This leads us to the next issue.

AUTOMATICITY AND PROBLEM SOLVING

An important contribution to the analysis of creative performance emerges from work in cognitive psychology on the everyday distinction between what are called controlled and automatic behaviors; or, in cognitive terms, controlled versus automatic processing. An analysis of this distinction is basic to an understanding of the acquisition and maintenance of skills of any sort, from playing billiards to setting up and solving differential equations. We are all aware of stages of acquisition of any nontrivial skill: At first, performance requires considerable effort, attention, and time of execution. As appropriate experience with the task grows, focused effort and attention may decrease as fluency increases; in other words, the task becomes "automatic." There are a number of classification schemes for distinguishing controlled from automatic performance. Here is but one abbreviated list descriptive of automaticity: (a) fluent, (b) effortless, and (c) unconscious. Of course, with any high-level skill, blends of controlled and automatic behaviors occur in dynamic interaction, as I will detail shortly.

What does behavior analysis have to say about these criteria for automaticity? As for fluency, an inherent property of response differentiation is that the reinforced response class increases in probability, including as we have seen, novelty itself. Alternative behaviors are selected out through extinction, induction, negative reinforcement, or punishment. In addition, fluency in performance may be explicitly selected by prevailing contingencies, including reductions in the delay and increases in the frequency of reinforcement. In a technique called precision teaching, fluency of a performance is explicitly trained by reinforcing only high *rates* of correct responses, as opposed to simply reinforcing some number correct (see, e.g., Binder, 1996; Marr, Thomas, Benne, Thomas, & Hume, 1999). The importance of such explicit training is not uncontroversial, but I should emphasize at this point that although with appropriate practice, a skill may be executed faster, the behaviors at the start of practice will be very different from those that emerge and predominate after practice. A highly developed skill is not by any means simply the original controlled performance done faster. This cannot be overemphasized.

With respect to effortlessness, response differentiation, for example, selects against what might be called "wasted motions." What constitutes a wasted motion, however, is a contextual issue. Deliberation and other mediating behaviors may be essential to the development of any significant skill, and, in a sense, are just as automatic as the subsequent practiced performance. At the time, they are more effective than the behaviors preceding them along the same dimensions characterizing automaticity.

An essential process in so-called effortlessness is the dynamical change in the nature of the behaviors at the beginning and final performances. New "units" may emerge from previous behaviors via the selection mechanisms already discussed, somewhat analogous to new species emerging through natural selection. How behavioral synthesis occurs in skill acquisition is an area of active research in behavior analysis as well as in fields like engineering psychology. This remains one of the great challenges in understanding behavioral change in general. Mechanisms of behavioral synthesis are inherent in concepts of intuition and insight, as we shall see.

Reflexive is another word for unconscious. Thus, somewhat paradoxically, reflexive has come to mean without reflection. For most behavior analysts, *consciousness* is a kind of icing on the behavioral cake, emerging from the acquisition of verbal behavior from a verbal community that shapes a self-descriptive repertoire. Loosely speaking, we are conscious to the extent we can describe our own behaviors, including private states, and perhaps some of the putative sources controlling these events. In the acquisition of some classes of skills, a self-descriptive repertoire may be useful. Thus we may self-instruct, "I should hold the club this way," or, "What am I doing right and what am I doing wrong?" This relatively private activity might be extended to more complex instructions as, "Perhaps I should use the methods of contour integration," or "Can I recall a problem I've solved that is similar to this one?" and the like. As high-level skills are developed, at least some of these kinds of supportive behaviors drop out, and we say the performance becomes unconscious—we simply perform. But of course, these performances are *not* the same behaviors we started with. Self-descriptive or self-instructive actions can be eliminated as control is gained from other sources and new behaviors are synthesized.

As behavior analysts, we begin with principles that characterize actions in which deliberation, self-description, and instruction necessarily play no part—any more than they would in a chemical reaction, the motion of a comet, or the appearance of a new species. As such we might speak of unconscious processes, yet basic behavioral principles do not cease to apply in the conscious mode; and, I will argue, these behavioral principles are essential to understanding issues of insight and intuition and thus some of the mysteries of genius. To begin to see this, we need to consider another important issue in behavior analysis.

RELATIONS AND RULES

So far in my approach to complex performance, I have emphasized behavior-change mechanisms involving selection by contingencies. As I alluded to earlier, stimulus control contingencies may be extended to include multiple terms that engender conceptual and relational control. A simple example is stimulus equivalence (e.g., Sidman, 1994). Without going into procedural details, subjects can be trained under a very limited set of conditions and relational control will emerge without additional training, surely an example of new response units shaped through contingencies. As mentioned earlier, relational control may involve enormous possibilities of abstraction. Simple relations such as "to the right of," "greater than," and "mother of" ultimately emerge into elaborate response classes encompassing similarity, contrast, hierarchical ordering, and so on—*relational frames,* to use Hayes' term (see, e.g., Hayes, Barnes-Holmes, & Roche, 2001), which we acquire to a greater or lesser degree of automaticity. The necessary and sufficient conditions for development of relational frames are a matter of considerable empirical and theoretical effort and controversy.

Consideration of relations and their descriptions leads naturally to another topic essential to the analysis of creative behavior, namely rule-governed behavior. Skinner (1969), in his analysis of problem solving, introduced the issue of contingency-controlled versus rule-governed behavior. After a latency of some years, this topic became one of the most active and contentious in behavioral analysis. As one might expect, the issue bristles with thorny complexity, and I will take no time here for the subtleties. Rules are powerful exemplars of the advantage of a verbal repertoire over acquiring behavior through direct contact with natural contingencies. It is clearly better to be told that a lion is a creature to be avoided than to learn, as they say, the hard way.

More in the present context, Mach reminds us in *Science of Mechanics,*

> When we wish to bring to the knowledge of a person any phenomena or process of nature, we have the choice of two methods: we may allow the person to observe matters for himself . . . or, we may describe to him the phenomena in some way, so as to save him the trouble of making anew each experiment. (1883/1960, p. 6)

Skinner (1969) said it this way some three quarters of a century later: "The point of science . . . is to analyze the contingencies of reinforcement found in nature and to formulate rules or laws which make it unnecessary to be exposed to them in order to behave appropriately" (p. 166).

The interrelation of rules and contingencies is a major, but often confusing, issue. Rules, in their origin, expression, and governance, as is the case of other verbal behavior, are acquired and maintained through contingencies imposed by the verbal community. Thus, rules are not contingency independent. That a contingency may act directly while a rule may exert its effect indirectly through a different set of contingencies means that contingency-controlled behavior will be different from rule-governed behavior, even though the two classes appear to have the same form. Moreover, descriptions of contingencies can rarely, if ever, substitute for the direct effects of the contingencies they describe. No one would wish to be operated upon by a so-called "surgeon" who had only read a book on surgery, no matter how detailed that book was. This analysis extends to verbal behavior itself. For example, you do not learn mathematics by reading about it; you must *do* it.

The distinctions between rule-governed and contingency-controlled behavior reflect some of the differences between controlled and automatic processing. Skinner (1969), without considering issues of automaticity, listed some contrasts reflected in the criteria I presented earlier: deliberation versus impulse; logical argument versus intuition; conscious versus unconscious actions; declarative versus procedural knowledge, knowing that versus knowing how; formula versus art; and so on.

As I will attempt to argue in the context of creative behavior, controlled versus automatic processing and rule-governed versus contingency-controlled behavior, as the ordering within these two contrasts might imply, are not unidirectional, but are, in fact, dynamically interactive in yielding truly complex and novel performances.

"HOW DO I GET TO CARNEGIE HALL?"

We need to deal with one more question before unfolding the implications of this tangled tale to scientific creativity. What factors control the development of automaticity? If we are considering any significant skill, two conditions are essential: some degree of consistency or coherence in the task and extensive practice. If the contingencies that control performance change randomly, there can be no skill development. Just how consistent the relations among behavior, context, and consequences have to be for automaticity to develop is a matter of some theoretical and empirical debate. Clearly, very complex creative performances of the kind we are interested in here must emerge from blends of consistent and varied contingencies so that only some components can achieve automatic status.

Given some degree of consistency, then the primary burden falls to practice. The old joke about the tourist in New York who asks the hipster, "How do I get to Carnegie Hall?" and gets the reply, "Practice, man, practice!" contains the essential truth about all significant creative achievements. Any viable account of creativity must place special focus on very extensive experience within a domain. Appropriate and persistent practice brings together all those factors I have discussed earlier as foundations for creative behavior.

Scientific biographies affirm this without exception. For example, Richard Feynman as a young high-school student learned mathematics by working through standard texts in trigonometry and the calculus, keeping elaborate notebooks of carefully worked problems. Rather than simply looking up or copying table values and functions, he calculated logarithmic and trigonometric values directly and derived tables of integrals for himself. By the time he entered MIT as a freshman, he had already mastered mathematics through the sophomore year and beyond (Mehra, 1996).

Perhaps the greatest mathematician of the 20th century, Srinivasa Ramanujan, as a 16-year-old worked through Carr's *A Synopsis of Elementary Results in Pure and Applied Mathematics,* a compendium of some 5,000 formulas, theorems, and so on, all presented largely without any indications of proof. Ramanujan supplied the proofs. It was said in response to his great work in number theory that every rational number was his personal friend. To quote his biographer Robert Kanigel (1991),

> Even in his published notebooks, you can see Ramanujan giving concrete numerical form to what others might have left abstract—plugging in numbers, getting the feel for how functions "behaved." . . . Numerical elbow grease it was. . . . Ramanujan was doing what great artists always do—diving into his material. He was building an intimacy with numbers, for the same reason that the painter lingers over the mixing of his paints, or the musician endlessly practices his scales. (p. 63)

I am reminded of Yeats' words:

> A line will take us hours maybe;
> Yet if it does not seem a moment's thought
> Our stitching and unstitching has been naught.

What are the consequences of such persistent, relentless, compulsive play? Simply stated, the result is a huge behavioral repertoire with complex units, associative links, and relational frames, all in a rich and deep dynamic blend. No wonder persons with these histories can seem magical in their powers. But it is magic gestated in the womb of toil, tens of thousands of hours of it. Weisberg (1993), for example, invokes what he calls the 10-year rule. Those deemed as outstanding creators worked intensively for at least a decade before producing works on which their reputations were built. This rule also may apply for significant works produced after a reputation is already established.

Wagner invested a quarter century off and on in writing the poem and composing the music to *Der Ring des Niebelungen.* Einstein in his "miracle year" of 1905 first published among other remarkable papers his special theory of relativity. This theory showed that the laws of physics must be the same for all systems moving uniformly relative to each other. To generalize this revolutionary accomplishment to systems in relative *accelerated* motion took immense effort. Not until 1916 did he publish a finished version of the general theory of relativity, a completely new theory about gravity and the cosmos, and to this day it survives every test thrown at it. Without question, it is one of the greatest accomplishments in the history of thought. Here is what Einstein said of the development of general relativity:

> In the light of knowledge attained, the happy achievement seems almost a matter of course, and any intelligent student can grasp it without too much trouble. But the years of anxious searching in the dark, with their intense longing, their alterations of confidence and exhaustion and the final emergence into the light—only those who have experienced it can understand that. (Tauber, 1979, p. 51)

The southern gothic writer Harry Crews expressed these conditions about another domain: "By the time a person even moderately masters any art form, it is almost too late to do anything else" (1993, pp. 14–15).

Even the creator may not appreciate what such a history may engender. The literature on creativity is replete with autobiographical descriptions of creative acts that seem startling to the creator, as well as others, because the sources are lost to them in a sea of experience. From this sea emerges *intuition.* Skinner (1974) has commented that "Behaving intuitively, in the sense of behaving as the effect of unanalyzed contingencies, is the very starting point of a behavior analysis" (p. 132). According to this view, intuition is an expression of contingency-shaped behavior. As I pointed out earlier in discussing the links between rule-governed versus contingency-shaped behavior on the one hand and controlled versus automatic processing on the other, these were interactive, not unidirectional. For example, the rules of mathematics, given the sorts of intensive histories we have described, seem to acquire dynamic properties that act as complex contingencies. A layperson may imagine the great mathematician at work starting with a set of rules and, step by step, generating one term or theorem after another in a kind of intraverbal chain of logic leading toward some esoteric conclusion. This is utterly mistaken.

The reality is more accurately described by Hardy in his description of how the young Ramanujan worked: "All his results, new or old, right or wrong, had been arrived at by a process of mingled argument, intuition, and induction of which he was entirely unable to give an account" (Hardy, Seshu Aiyar, & Wilson, 1962, p. xxx). This kind of pattern also applies to less lofty mathematicians as well, as Feferman notes:

> The mathematician at work relies on surprisingly vague intuitions and proceeds by fits and starts with all too frequent reversals. Clearly logic as it stands fails to give a direct account of either the historical growth of mathematics or the day-to-day experience of its practitioners. (quoted in Davis & Hersh, 1981, p. 357)

Andrew Wiles, who spent more than 7 years alone working on the proof of Fermat's Last Theorem, describes his experience in terms of encountering a dark unexplored mansion:

> One enters the first room of the mansion and it's dark. Completely dark. One stumbles around bumping into furniture, but gradually you learn where each piece of furniture is. Finally, after six months or so, you find the light switch, turn it on, and suddenly it's all illuminated. You can see exactly where you were. Then you move into the next room and spend another six months

in the dark. So each of these breakthroughs, while sometimes they're momentary, sometimes over a period of a day or two, they are the culmination of, and couldn't exist without, the many months of stumbling in the dark that precede them. (Singh, 1997, pp. 236–237)

Mathematicians, it seems, also engage in the stitching and the unstitching.

Further consequences of the interplay between contingency-controlled and rule-governed behavior fueled by extensive experience is a topic I will not further elaborate upon here. Suffice it to say that one can also apply this analysis to the historical evolution of abstraction in mathematics and physics (see Marr, 1986, 1995).

Where have we come so far in this analysis of creativity? Beginning with Weisberg's view of creativity as problem solving, I've indicated how basic behavioral processes of response differentiation and stimulus control can result in complex stochastic and dynamic webs of associative links that may, in turn, engender novel behavior. One can think of a spider web on which a slight tug at any one point may exert variations in effects at many distant points. This dynamical web is continually modified and extended through intensive, long-term interaction with a knowledge domain that provides not simply an enormous repertoire of knowledge and skills but also automaticity at least to the level of elaborate relational, rule, and heuristic-based performances. These performances act functionally as if directly controlled by the contingencies related to the problem at hand. Given these conditions, a person's ability to manipulate the domain to generate problems as well as their solutions will, to the uninitiated, appear as astoundingly magical. Arthur C. Clarke once said that any sufficiently advanced technology would be indistinguishable from magic. What is it about so-called geniuses that allow them to attain this "advanced technology" of creativity? This question leads to the contentious issue of individual differences.

THE PROBLEM OF INDIVIDUAL DIFFERENCES

Two major issues here are well known, but neither is clearly resolved. The first is the role of heredity in outstanding creativity—genius, if you like. Galton was the first to investigate this systematically, but his interpretations and methodologies have been deeply questioned. However, virtually no one doubts the hereditary contributions to major creative achievement. Recent cogent arguments have emphasized the role of *emergenesis,* that is, whatever the hereditary factors are contributing to creative behavior, they must constitute a special and thus rare configuration (Eysenck, 1995; Simonton, 1999). Emergenesis predicts that genius would *not* run in families, and, in general, this is the case. So it seems possible that the emergent aspects of significant creativity are dependent on emergent hereditary processes.

The second and perhaps related issue is whether or not one can reliably characterize a creative personality, that is, a relatively stable configuration of behavioral tendencies shared by persons of creative eminence. Unfortunately, space prevents my discussion of all the controversies here. Because Weisberg believes that the notion of "genius" is a myth, he would have to show that no such personality patterns exist. His arguments based on psychometrics and other issues are compelling, if not convincing; but in my view at least, significant mysteries remain unaccounted for by any approach.

Weisberg treats the issue of individual differences first by appealing to domain-specific skills, perhaps innately determined, but in any case supported by environmental contingencies. In addition, of course, these skills must be developed to extraordinary expertise, as we have seen. These conditions are certainly illustrated by the biographies of eminent scientists and mathematicians, as well as those in other fields. But as the development of expertise implies, there must be extraordinary motivation and commitment. From my point of view, no approach has provided much enlightenment here. As behavior analysts we know something about how to develop extended performances under conditions, for example, of intermittent reinforcement. Nevertheless, such procedures usually require the selection and arrangement of appropriate conditioned reinforcers. What were the sources of reinforcers for Newton, Faraday, Gauss, Euler, Maxwell, Boltzmann, Einstein, Bohr, or Ramanujan? Some answers emerge from biographies, including the perhaps-unpopular fact that extrinsic reinforcers typically play major roles. In fact, sources are generally numerous and varied. In the cases of Newton and Ramanujan, for example, religious and mystical elements contributed to their work. Moreover, simply gaining control over some domain and manipulating it to achieve further control can supply moment-to-moment consequences—intrinsic reinforcers, if you like. Much has been written of the basic *aesthetic* quality of science and mathematics. Anyone who has done either knows something of what this is about, but most people are unmoved by the beauty in Fermat's Last Theorem or the eerie quality of some of Ramanujan's theorems, even if they understand what they say. They would certainly be perplexed by Paul Dirac's assertion that it is more important to have beauty in one's equations that to have them fit an experiment; or Einstein's comment, "For me the general relativity was simply too beautiful to be false." Fortunately for Dirac and Einstein, most of their major works were both beautiful and wonderfully true.

Aesthetic reinforcers require a whole analysis of their own, but surely the sort talked about by Einstein and many others emerges from extensive play of the kind I detailed earlier. In other words, the effectiveness of aesthetic reinforcers must depend heavily on successful encounters with the relevant material. Moreover, the powerful role of domain-specific skills is found simply in the fact that what we do well, we tend to do more of. This is, of course, nothing more than a restatement of the principle of reinforcement, and we come full circle back to behavior analysis—a theory simply too beautiful not to be true.

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