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Human creativity as a function of chaotic dynamics: Implications for research and practice in education

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HUMAN CREATIVITY AS A FUNCTION OF CHAOTIC DYNAMICS: IMPLICATIONS FOR RESEARCH AND PRACTICE IN EDUCATION

by

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A DISSERTATION

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APPROVED: Leonora B. Marx Cohen
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Currently investigators in many scientific disciplines are studying the behavior of nonlinear dynamic systems. Prigogine has shown that such systems, when pushed far from equilibrium, can abruptly and spontaneously self-organize to a new level of complexity or information, a level to which something has been added that was not inherent in the system prior to self-organization. Such self-organization would seem to be the prototype of creativity.

This study sought to investigate human creativity utilizing the insights afforded by current understandings of nonlinear, nonequilibrium dynamics. Taking as a basic assumption the idea that creativity originates as a function of brain dynamics, current neuroscientific literature was examined to determine whether the brain can legitimately be viewed as a nonlinear dynamic system. Evidence gathered strongly supported this view. Having established a physiological basis, current theories of creativity were examined to determine whether the nonlinear dynamic perspective could provide a more coherent, comprehensive, and compelling explanation of human creativity than do other currently existing theories and models.

Implications for nurturing creativity in educational environments are discussed, both in regards to particular classroom strategies and overall philosophy. In particular the nonlinear dynamics perspective suggests that strategies which allow exploration far-from-equilibrium may be beneficial to developing creativity. However, the perspective also suggests that balance is required between free exploration and acquisition of knowledge and skills. Many strategies already employed for teaching talented and gifted students have these attributes.

Possibilities for future research are suggested, such as attempting to establish a link between electrophysiological brain states and cognitively experienced creative moments. This might be done through isolating strange attractors from brain mapping data. Further investigation, based on the nonlinear dynamic perspective, is also needed to develop new instruments for assessing creative potential.

Another possible avenue of research might be to investigate the effects of far-from-equilibrium exploration on not only creative potential, but also on self-esteem.

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DEDICATION

To my Dad, with all my love

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CHAPTER I

INTRODUCTION

Statement of the Problem

The objective of this dissertation is to explore the phenomenon of human creativity from the perspective afforded by the new theories of nonlinear dynamic systems. This exploration will be geared to answer several questions.

Question 1: Can the new insights afforded by the science of complex nonlinear dynamic systems (popularly known as Chaos Theory) shed light on brain function, particularly creative brain function? Understandably, such a study is hindered by the rather rudimentary knowledge we have of how the unimaginably complex human brain works. Current technology cannot begin to delineate the exact neuronal processes involved in thought, much less creative thought. However, fruitful analogies can be drawn between the complex, nonlinear brain system and other complex systems which have been successfully modeled.

> Systems giving rise to transition phenomena, long-range order, and symmetry breaking far from equilibrium can serve as an archetype for understanding other types of systems that show complex behavior--systems for which the evolution of laws of the variables involved are not

> known to any comparable degree of detail. (Nicolis & Prigogine, 1989, pp. 217-218)

Question 2: Can the behavior of complex nonlinear systems be used to shed light on human creativity viewed at the level of behavior? Do the insights afforded by the study of chaotic dynamics provide a more coherent and compelling explanation of human creativity than other currently existing theories and models?

Question 3: Can these insights find application in education, and if so, to what extent? In particular, how can an understanding of nonlinear dynamics help the classroom teacher encourage creative responses? Does an understanding of chaotic dynamics support or deny current educational practices, such as Clark's (1988) integrated learning, reader response theory, individualized instruction, or direct instruction? Will an understanding of the behavior of complex systems cause us to modify the way we think about individuals and their behavior?

The Critical Importance of Creativity

Why is creativity important, particularly at this moment in history? An illustrative analogy is provided by a comparison of the behavior of two species of ants, *Tetramorium impurum* and *Tapinoma erraticum*. These two species have been shown to have distinct foraging patterns. While both groups utilize scout ants to find food sources and lay a trail for others in the nest to follow, the efficiency with which the trail is followed to the food source differs greatly between the two groups. Those of the _Tapinoma_ species are seventy-five percent efficient in following the trail of a scout ant back to a discovered food source. Only about nine percent of the _Tetramorium_ succeed in following the trail to the food source. At first glance, it would seem that the _Tapinoma_ species has a survival advantage over the _Tetramorium_, and the random wandering behavior of the _Tapinoma_ would appear to be a dangerous tendency. However, researchers discovered that when multiple food sources are available in an area, the seemingly inefficient random wanderings of the _Tetramorium_ allow a far greater probability that they will efficiently find and utilize all available food sources simultaneously, rather than exhausting one source before looking for another (Nicolis & Prigogine, 1989).

Upon reflection, the _Tapinoma_ species is well suited to survival in an environment in which the sources of supply are stable and identified. However, the _Tetramorium_ are clearly better adapted to environments which hold surprises, which are unstable, and which consequently reward innovative wanderings.

An analogy can be drawn between the behavior of these ants and humans. Now, at the end of the twentieth century, we human beings must assess our behavior in light of the enormous changes occurring everywhere. For example, during most of this century, we in the industrialized world have made a virtue out of efficiency, in many instances placing its importance well ahead of innovation. The result is usually characterized by uninteresting and certainly unimaginative products that are manufactured with extreme speed. A visit to any fast-food establishment provides a good example. The food may have nutritional value in the form of calories, but for most adults who have had the good fortune to taste food prepared with care and imagination, the primary appeal is that the food comes quickly.

In the field of education, strategies such as DISTAR (Becker, 1986), which provide teachers with materials and rigid scripts, serve a similar purpose. The appeal for some educators is that these strategies are purported to increase the efficiency of learning, and are less dependent on the proficiency of teachers for effective implementation. The drawback is that students are given little chance to develop their own problem-solving strategies, and no chance to experiment with new ideas.

Strategies aimed at such efficiency, resembling those of the <u>Tapinoma</u>, have worked admirably in relatively stable situations where necessary sources were identified and available and we knew just how to exploit them. But now, on the leading edge of the twenty-first century, we see evidence of great instabilities. Fossil fuels are running out and nuclear power is proving dangerous. Global warming threatens agriculture at a time when the world population is exploding. The thinning ozone layer threatens to destroy the most basic layer of the food chain, thereby threatening all life on this planet. Psychologically unbalanced despots threaten to unleash nuclear and biological warfare.

Whether we (and this planet) survive depends on our finding effective answers to these and similar problems. This will require creative, highly innovative, flexible adaptations to the challenges we all face. These creative answers will not come from following the old trails. Those routes will lead us only to the exhausted sources, and the old, failed answers. We need, at this crisis point in history, to take our cue from the *Tetramorium*. We must encourage capable individuals to wander far from the beaten paths in search of new sources and new answers. We need to recognize that not all wanderings will be fruitful. We must encourage bright minds to take the risk of being wrong in order that some among the new foragers will blaze new and fruitful trails.

Declaration of Perspective

All scientific inquiry is carried out within the framework provided by a conceptual lens. A conceptual lens is a network of basic assumptions regarding the nature of reality that influences the way phenomena are perceived (Cohen, in press-b). This concept is similar to that referred to by Overton (1984) as a world view. Currently, the research carried out on complex nonlinear systems is influenced by the materialist lens. Briefly stated, the materialist viewpoint asserts that everything in the universe is made of matter. Thus consciousness, or mind, exists only as an emergent phenomena of matter (Goswami, in press). This dissertation proposes to explore the extent to which this materialist perspective can provide a satisfactory explanation for human creativity.

Methodology

Interdisciplinary Conceptual Research

Like the Tetramorium in search of new sources, this dissertation will utilize new paths, those provided by interdisciplinary conceptual research, to investigate human creativity. Broadly conceived, there are two possible configurations which can be used in the pursuit of interdisciplinary research. The most common form is to bring together two or more individuals from different disciplines to focus their knowledge on a particular problem. Corporate and governmental "think tanks" are a prime example. The other possibility is that a single individual investigates a concept or problem through accessing the expertise of various experts representing different disciplinary backgrounds. The group model is by far the most accepted form. However, the group model poses difficulties:

> Bringing together professionals with different disciplinary affiliations generates profound problems of interpersonal communication. These problems arise not only from the different languages of the participating disciplines, but also from the differential evaluations (that is, differential status) of the disciplines and of the individual professionals. (Anbar, 1986, p. 155)

Rossini and Porter (1984) and Klein (1990) also note that team selection, number of individuals on the team, and diversity of perspective among team members are all factors that affect the outcome of the research project.

Interpersonal problems can be avoided when interdisciplinary research is carried out by a single individual. However, there are some strong criticisms against proposing such a model. The most immediate response to such a suggestion is that it is difficult enough to garner expertise in one small area of one discipline, much less two or more. Thus research conducted by such an individual would be superficial at best. Donald Campbell (1986) answers this objection:

> Lying behind many models of interdisciplinary competence is an unrealistic notion of unidisciplinary competence--the image of scholars competent in one discipline. It will clarify the discussion of interdisciplinary competence to recognize at the outset that there are no such persons. What we have instead are congeries of narrow specialties each one of which covers no more than one-tenth of the discipline with even a shallow competence. Yet individual disciplines do have some integrity, some comprehensiveness. . . . What must be recognized is that this integration and comprehensiveness is a collective product, not embodied within any one scholar. (p. 32)

Despite Campbell's defense, the criticism of superficiality needs to be defused by demonstrating that an individual can, through interdisciplinary research methodology, make a valuable contribution to theory building and to the corpus of scientific knowledge.

Interdisciplinary Research Methodology

Given that very few individuals can, in one lifetime, attain mastery of more than one subject area, how does one conduct interdisciplinary research without succumbing to superficiality? In the same way that lawyers, literary critics, theologians, philosophers and historians have always conducted research: one makes use of the expert witnesses from various disciplines. For example, consider a medical malpractice lawyer who is asked to argue a case concerning a surgery that leaves a patient paralyzed. The lawyer does not have extensive medical training, and cannot without help muster appropriate arguments. If this lawyer is shrewd, s(he) will have delved far enough into the subject to be able to recognize what kind of expert testimony is needed, how many perspectives are required to carry the argument, and who is most likely to have the information. The lawyer's role is then to synthesize the testimony of the experts in such a way as to support the argument, account for all available data, and satisfy the questions and objections of those on the opposing side.

Admittedly the lawyer is biased, and this bias is openly declared. Since investigators, as human beings, are inescapably biased, they must declare their orientation or conceptual lens overtly, thus providing context within which others can better understand their argument (Borland, 1990). Unlike lawyers, who by law must do everything possible to support the argument in favor of their client, interdisciplinary researchers must not "hide" or ignore evidence which would falsify their theory. Contradictory evidence must be brought forward and dealt with. The purpose is not to "win," but rather to offer new ideas into the arena of scientific discussion.

If one is to conduct an investigation utilizing the aid of experts, how is this to be done, and at what stage in the investigation? One way, of course, would be to seek out individuals from different disciplines, talk to them, perhaps work with them. An alternative is to mine the literature for everything relevant to the investigator's area of interest. This is a method already used within disciplines, and is referred to as a "review of the research." The difference is that in pursuing interdisciplinary research one must be open to the different conceptual lenses underlying basic assumptions, and be prepared to immerse oneself in a different perspective. A rough analogy, but one that has merit, is to consider the difference of learning a new language by moving to a new country and immersing oneself in the language and culture versus taking a course on conjugating verbs and accumulating vocabulary. By immersing oneself in the new culture and language of another discipline, and by approaching the experience with openness and a certain amount of humility, one is more likely to achieve a synthesis of the new perspective with one's own.

Issues Concerning Choice

The problem of choice is crucial to the character of the study, and will invariably involve bias, as demonstrated above. In the olden days (and how far back one has to go to find the "olden days" depends on one's field), one was expected to read all literature pertinent to a particular question. This ideal is now generally acknowledged as unattainable, and therefore every investigation involves the choosing of some avenues of evidence over others. Clearly, the choices one makes regarding possible evidence greatly affects the character of the study. Nauta (1984), speaking of choosing team members for interdisciplinary research says:

> Your selection and co-ordination of concepts (theory) depends on your selection and co-ordination of disciplines and experts (organization), and vice versa. In view of its central importance in the context of interdisciplinarity, that thesis of the interdependence of organization and theory can be called the first law of interdisciplinarity. (p. 6)

Nauta is speaking of the feedback relationship between the investigation and the investigators. Such a relationship is nonlinear (see Chapter II), meaning that the game itself changes as a result of its being played.

The nonlinear relationship between research question and expert evidence is a crucial aspect of interdisciplinary team research, and figures equally in research conducted by an individual. In this respect, individual research has an advantage over team research in that an individual can access as many different disciplines and perspectives as seems relevant and/or interesting. Nauta (1984) points out that team research must achieve a compromise between the ideal of involving as many kinds of experts as possible and the reality that the greater the number of individuals involved the greater the potential for interpersonal conflict.

The Issue of Dependence on Outside Investigators

A common feeling among scientific investigators is that basing one's own work upon a foundation laid by others is a dangerous business at best. After all, the published report of research rarely discloses the messiness that seems to accompany most investigative efforts. How is one to know how reliable the results actually were unless one replicates the experiment? Such a perspective reveals the skepticism which has served to uphold the rigor of scientific inquiry processes and has helped to minimize the number of errors passed on from one investigation to the next. However, few scientist can say that they prove every basic assumption upon which their study is founded. Indeed, many individuals are not even aware of these basic assumptions. Conclusions reached through empirical means come to be accepted as "truth" when enough corroborating evidence is amassed. This represents a practical compromise between trying to prove every assumption and accepting at face value the published results of every researcher. The point here is that, in general, research is conducted which derives its conceptual base from the work of others.

Patricia Churchland (1986), a philosopher who has chosen to integrate the findings of neuroscience with the insights of philosophy, provides an example of a single individual pursuing interdisciplinary research by relying on the expertise of those in a different discipline. She addresses the problem of dependence on other scholars in the preface to Neurophilosophy:

> Given the range of topics I needed to know about, I was throughout the project dependent on the willingness of neuroscientists to explain their research. . . . From time to time I found considerable disagreement among neuroscientists on fundamental issues, and at first I tacitly assumed that there must be someone who really knew what was what and who could settle for me what is the Truth. In the end I knew that I had to make up my own mind, and do it in the way that any neuroscientist would: find out as much as I reasonably could about the issue and go with what seemed most reasonable. A vague decision procedure, to be sure, but the only one I know of. (p. x)

In this era of information explosion, Churchland (1986) has made a reasonable compromise. Her search for philosophical grounding led her to the neurosciences, a field as far removed from philosophy as imaginable. Lacking the years of study needed to perfect laboratory technique, she was forced to rely on the findings and insights of those who have chosen to investigate intensively the narrow and precise questions. The information she gleaned in her studies, coupled with her own expertise in philosophy, resulted in an exciting and novel approach to the age-old problem of epistemology.

Advantages of This Methodology

This study has included immersion in the literature concerning nonlinear dynamics, creativity theory, brain function, and educational theory, plus digressions into such areas as physics, neural networks, evoked potentials, and philosophy. Such an approach is justified on several counts.

1. The current fragmentary trajectory of single discipline scientific research contributes to the information explosion without adding significantly to a useful synthesis of ideas or a larger perspective.

2. Many of the current areas of interest cross disciplinary boundaries. Brain structure and function is just one example. Others abound in such areas as ecology, the social sciences, and any other area which studies systems. An interesting aspect of systems is that their boundaries are arbitrarily assigned, usually as a result of conceptual lenses.[1] If we redefine a system to include what we once thought of as external, then we are likely to discover that we need to step across disciplinary lines to study those systems adequately.

[1]See Bateson (1979) for a discussion of mind as immanent in the interaction of a person and the environment.

3. Conceptual lenses, propagated and supported by the assumptions and views of the various disciplines, have a tendency to constrain ideas and leave one languishing in conceptual ruts. Since Archimedes stepped into his bath and yelled "Eureka," it has been recognized that great discoveries usually are a result of shifting perspectives. Currently, there are several groups who make lots of money demonstrating how to become more creative problem solvers by purposefully changing perspectives (see, for example, Adams, 1974; Isaksen & Treffinger, 1985; Osborn, 1963). Interdisciplinary research facilitates attainment of a new perspective, or the integration of two perspectives, and therefore increases the likelihood of new and potentially great discoveries.

4. The oft-cited criticism that one must be an expert in one's field in order to make any seriously valuable contribution is challenged every time some neophyte, equipped with the perspectives garnered from another discipline, steps in and solves a problem that has the experts stumped. Watson and Crick did this in solving the DNA puzzle (Birnbaum, 1986).

5. Interdisciplinary research "offers us a way in which the richness of our experience can be integrated and it forces us to rely upon the works of others, thus breaking

down artificial barriers and building a broader sense of collegiality" (Schwartz, 1988).

6. Interdisciplinary research that successfully synthesizes the knowledge and perspectives of two or more fields has been successfully conducted in the past, and the results provide fascinating reading. Examples are Patricia Churchland's (1986) synthesis of neuroscience and philosophy as revealed in Neurophilosophy, James Gleick's (1987) wide-ranging Chaos, and Briggs and Peat's (1989) Turbulent Mirror. The popularity of PBS series such as Ascent of Man, Connections, and The Day the Universe Changed attests to our hunger for the grand synthesis.

The final justification lies in the basic purpose of scientific investigation, which is to foster discussion among scientists in the belief that, as the discussion develops, our understanding of ourselves and our relation to everything around us will be enriched. There is much to suggest that "reality" is a construct mediated through the human mind (Bateson, 1979; Churchland, 1986). If we cannot directly access reality, we must approximate it through the accumulation of corporate efforts. Theories, even great theories, such as Ptolemy's model of the universe and Newton's theory of gravity, rarely survive intact. Their purpose is served when they spark discussion which leads to further discovery. In this way even theories that are later proved wrong help to further our quest for knowledge. As Churchland (1986) says: "This is the frontier, after all, and it is to be expected that there will be rough edges, false starts, and considerable theoretical derring-do" (p. 153).

Organization

Chapter I provides an introduction to the dissertation, including a rationale for supporting creative endeavor. Also included is a statement of the questions that prompted this study. Since the study is conceptual in nature and has relied extensively upon literature from a variety of disciplines, there will be no chapter devoted to a literature review. Instead, literature will be reviewed and cited throughout this dissertation.

Chapter II will discuss aspects of nonlinear chaotic dynamics pertinent to this study of creativity. Nonlinear dynamics is a newly emerging area of science, and many of the concepts and much of the vocabulary used in the remainder of the dissertation may be unfamiliar to some readers. Much of the specialized terminology will be defined in this chapter.

Chapter III will delve into the nonlinear aspects of cortical brain function. This will provide a foundation for the assertion that brain dynamics can justifiably be viewed in terms of chaotic dynamics.

Chapter IV will offer a possible description of the creative process based on nonlinear chaotic dynamics. This description will then be compared with currently compelling theories of creativity in an attempt to determine whether this new view maintains its explanatory power in the face of the generally acknowledged phenomena associated with the creative act. For the purpose of this dissertation, "creativity" will generally refer to the process involved in the generation of novelty. Thus the focus is on behavior rather than product.

Chapter V will address some of the educational implications afforded by nonlinear dynamic systems theory, particularly as it pertains to creativity. This chapter will not include an exhaustive list of possible applications. The study of complex nonlinear systems is relatively new, and will continue to be a rich source of innovation in the decades to come. It is not now possible to imagine all the implications arising from this study of complex systems.

Chapter VI will provide a brief summary, along with suggestions for further areas and methods of inquiry. Also discussed will be the limitations of this study.

CHAPTER II

COMPLEX SYSTEMS AND CHAOTIC DYNAMICS: CRUCIAL CONCEPTS AND DEFINITIONS

Introduction

A promising new trail is currently being blazed by investigators studying complex, nonlinear systems. The pioneers are those from disciplines as diverse as physics, biology, mathematics, neuroscience, philosophy, economics, meteorology, and psychology, who have begun to move beyond the classical, strictly reductionist approach to science. Instead, they are studying complex, nonlinear systems, not as mere aggregates of simple components, but rather as holistic entities which exhibit their own distinct patterns and behaviors (Briggs & Peat, 1989; Gleick, 1987).

As the principles underlying the behavior of nonlinear systems are being discovered, researchers are struck with the similarity of process revealed by systems that show no structural similarity. Thus biologists interested in population dynamics and chemists studying chemical clocks are discovering that the findings of each are germane to the questions of the other. Inquiry through analogy is becoming an accepted starting place for studying the behavior of systems that have thus far proved too complex to yield their secrets to more classical approaches (Nicolis & Prigogine, 1989; Siler, 1990). The popular rubric under which complexity is studied within the different disciplines is Chaos Theory.

Chaos Defined

The Oxford English Dictionary defines chaos in two ways: The first is "the 'formless void' of primordial matter, the 'great deep' or 'abyss' out of which the cosmos or order of the universe was evolved." The second reflects the more common usage, namely, "a state resembling that of primitive chaos; utter confusion and disorder. Anything where the parts are undistinguished; a confused mass or mixture, a conglomeration of parts or elements without order or connexion." For those unacquainted with Chaos Theory, the thought of studying chaos seems ludicrous. Science, after all, seeks to discover order, not celebrate disorder. However, for those who currently study chaos, the first definition is strangely powerful. For them, chaos is the seemingly orderless and meaningless confusion out of which, when viewed from another perspective, or at a higher level of description, order mysteriously appears. An easily grasped example is provided by Freeman (1991):

> The activity of commuters dashing through a train station at rush hour resembles chaos in that although an observer unfamiliar with train stations might think people were running every which way without reason, order does underlie the surface complexity: everyone is hurrying to catch a specific train. The traffic flow could rapidly be changed simply by announcing a track change. In contrast, mass hysteria is random. No simple announcement would make a large mob become cooperative. (p. 83)

Basic Concepts

Chaos is behavior that naturally and spontaneously arises in systems in which the governing equations are nonlinear, and which possess more than one degree of freedom.[1] While it appears to be random, there is a distinct difference between chaotic dynamics and random behavior.

> Randomness arises when there is no connection between one event and the next. Like flipping coins, the final position of the coin on one flip has no correlation to its position on the previous flip, or any flip before. But in chaotic determinism, any given position is directly related (caused) by previous events. (Haken, 1983, p. 22)

Most naturally occurring systems, including biological systems, are nonlinear (Davies & Gribbin, 1992; Gleick, 1987; Nicolis & Prigogine, 1989).

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[1]A degree of freedom is represented by each independent variable which helps define the state or behavior of a system, such as temperature, pressure, and so forth.

Nonlinearity

A linear system "is one in which the whole is equal to the sum of its parts, and in which the sum of a collection of causes produces a corresponding sum of effects" (Davies & Gribbin, 1992, p. 44). A nonlinear system, in contrast, is one in which values measured within a system depend in a complicated way--not just proportional to, or differing by some constant--upon values measured in an earlier state (Rasband, 1990). Davies and Gribbin (1992) provide a simple illustration to underline the distinction between linear and nonlinear relationships:

> If water is dripped onto a dry sponge, the weight of the sponge will increase. The weight increase will at first be proportional to the number of drips: twice the number of drips causes twice the increase in weight. This is a linear relationship. But when the sponge gets very wet, it will start to saturate. In this state, its capacity to absorb more water will be reduced, and some of the water that drips onto it will run off again. As its capacity to absorb water declines, the weight increase becomes nonlinear--progressively less, in this example, for each additional drip. Eventually the weight will stabilize and become independent of the number of additional drips, because each new drip being added to the sponge is balanced by the same amount of escaping water. (p. 45)

Feedback

In nonlinear systems, particularly biological systems, one source of nonlinearity is provided by feedback. Feedback occurs when the output of a system's behavior influences the further functioning of the system, and by doing so provides crucial regulating influences. Feedback can be thought of as negative if it serves to control a system. Positive feedback, in contrast, amplifies the output of a system. A household thermostat provides a good example of negative feedback. Set to keep the house between 69 and 71 degrees, the furnace will turn on when the thermostat records temperatures below 69 degrees. As the furnace pumps heat into the house, the temperature rises until it exceeds the cut off point of 71 degrees. At this point the furnace shuts off, and the house is allowed to cool, until the temperature falls below 69 degrees.

An example of positive feedback occurs when a microphone is placed too close to a loudspeaker. The output from the speaker is picked up by the microphone, amplified and sent back through the speaker, where it is again picked up by the microphone. This results in the unwelcome screeches we have all experienced (Briggs & Peat, 1989). Instances of feedback in the human system are easily found. For example classroom teachers trained in behavioral modification use negative feedback (i.e., punishment) to extinguish undesirable student behavior and positive feedback (rewards) to stimulate performance.

Sensitive Dependence on Initial Conditions

Another aspect of the nonlinearity of chaotic systems and perhaps the driving force behind chaotic dynamics is a phenomenon referred to as <u>sensitive dependence on initial conditions</u>. When a system is sensitive to initial conditions, there is the tendency for the outcome of an event to be markedly altered by very slight changes in a single variable. A simple mechanical example will illustrate this principle. Imagine holding a steel ball directly above, and in perfect alignment with, a vertical razor blade that has been anchored to a table. When the ball is released and falls upon the razor blade, it will be deflected to one side or the other. Which side it falls on depends exquisitely upon the most minute conditions affecting each trial, and cannot be predicted in advance (Haken, 1983).

This phenomenon was first described by Henri Poincaré in 1903:

> It may happen that small differences in the initial conditions produce very great ones in the final phenomena. A small error in the former will produce an enormous error in the latter. Prediction becomes impossible, and we have the fortuitous phenomenon. (Cited in Crutchfield, Farmer, Packard, & Shaw, 1986, p. 48)

This observation by Poincaré was largely ignored until Edward Lorenz rediscovered this phenomenon while modeling weather patterns on a computer. Using the computer, Lorenz could run his weather program several times starting from nearly identical initial values, but including a minute change in the value of one input parameter. He expected that the minute change in initial conditions would either result in no change in the overall weather pattern, or would demonstrate a change in pattern proportional to the magnitude of change in the input. To his surprise the tiny change in initial values quickly resulted in enormous changes to the weather pattern. In other words, the "error" introduced grew exponentially in time, rather than linearly. This phenomenon is referred to metaphorically as the "butterfly effect," referring to the theoretical ability of the small local disturbance caused by a butterfly flapping its wings to cause massive changes in global weather patterns within a relatively short time (Gleick, 1987).

The necessary corollary to the butterfly effect is that one cannot predict the future behavior of a chaotic system. To do so, one would have to determine the initial conditions with infinite precision. The impossibility of such a determination does not so much lie in human limitation, but rather in the nature of the real numbers used to define the values of initial conditions. Most real numbers can be expressed only by a decimal followed by an infinite string of random digits. According to Davies and Gribbin (1992):

"It follows that to specify even one such number involves an infinite quantity of information" (p. 40). Therefore, precision in defining initial conditions is, in principle, impossible.

The concept of sensitive dependence on initial conditions has intrigued physicists and mathematicians accustomed to dealing with relatively simple systems. However, it becomes awkward for those describing complex, dynamic natural systems. How can a meaningful initial point be chosen for a living entity? One has to consider an initial point which continually moves through time. This is also awkward, since in such a case the word "initial" loses its meaning. Instead, in the case of a nonlinear dynamic system open to the environment, and subject therefore to the vicissitudes of nature, a more meaningful concept is that of extreme sensitivity to changes in variables.

As a final note, while these systems are fundamentally unpredictable, there is necessarily a range of behavior beyond which the system cannot stray (Davies & Gribbin, 1992; Gleick, 1987). This allows the system to be predictable in a global and statistical sense, but not in particulars. For example, one may not know exactly how an individual will respond to her first taste of chocolate, but the behavior exhibited will be recognizably human.

Behavioral Characteristics of Chaotic Systems

Complexity

The exciting aspect of the behavior of nonlinear systems subject to sensitive dependence on initial conditions and therefore fundamentally unpredictable, is that they demonstrate complex behavior: behavior that is at times intrinsically different from behavior displayed by the system previously. But what constitutes complex behavior? How complex does a system have to be to demonstrate chaotic dynamics? What exactly is meant by the word complexity? How complex is complex?

The first distinction that needs to be made is between the complexity of system structure and system behavior. A structurally simple system such as a pendulum can exhibit complex behavior when nonlinear constraints are applied (Briggs & Peat, 1989; Gleick, 1987). On the other hand, structurally complex computers behave in completely predictable, simple, linear fashion. Apparently the number of components comprising a system does not guarantee complex behavior. Rather, it is the nonlinear interaction between and among components that gives rise to complexity. Biological systems, which are nonlinear--and in particular highly evolved systems such as the human brain--are invariably complex in both structure and behavior.

According to Pagels (1988), complex systems lie on the continuum between simple linear systems (such as a diamond crystal) and systems exhibiting completely random behavior, such as gas molecules in a cloud. The behavior of simple, completely ordered systems is easy to predict and understand. Completely random systems are also relatively easy to understand when statistical methods are applied. True randomness "guarantees very stable average behavior so that we can find appropriate laws" (Pagels, 1988, pp. 54-55). Complex systems, on the other hand, are more difficult to understand, and their behavior is frequently unpredictable. Pagels, following the work of A. Kolmogorov and G. Ghaitin, measures the complexity of a system by the length of the shortest program necessary to compute the behavior of the system (see also Nicolis & Prigogine, 1989). For a complex, dynamic, nonlinear system, the behavior of which is fundamentally unpredictable, the length of the algorithm necessary to describe the behavior of the system is infinite.

One important measure of complexity is that of information generated by the system. If data collected about a system is always the same, then it provides no new information about the state of the system. If data collected show differences, then clearly new information is being generated by and can be gleaned about the system. This is assuming, of course, that one is asking the right questions and collecting data appropriate to reveal the state of that system. For example, when I ask my kindergartner what he did at school, I always receive the answer, "Nothing." Day after day the same question elicits the same response, and I receive no new information about his state. However, when I ask him what he liked best at school today, I get an enthusiastic response detailing the many activities that he liked (or did not like). A stable system reveals, by definition, no new information. But a system subject to instability and chaotic dynamics reveals a constant stream of information.

Self-Organization in Nonlinear Dynamic Systems

Up to this point, nonlinear systems have been described which are sensitive to initial conditions, and which are therefore fundamentally unpredictable. Such systems behave, from time to time, chaotically. Few would argue with the proposition that much natural phenomena falls into the category of complex, unpredictable systems, the behaviors of which are impossible to reduce to simple algorithms. So what makes chaos fascinating rather than merely frustrating? The fascination lies in the propensity for such systems to be <u>self-organizing</u>.[2] This is a term used by chaologists to describe a process by which a system in a far-from-equilibrium state undergoes an abrupt transition to a much more elaborate and complex state or level. The newly attained state tends to be stable, at least until it is again driven to another far-from-equilibrium crisis (Davies, 1988; Nicolis & Prigogine, 1989; Prigogine & Stengers, 1984).

Before continuing, some discussion of equilibrium and non-equilibrium states is necessary. According to Nicolis and Prigogine (1989), systems open to their environment achieve equilibrium when there is no exchange between system and environment due to the fact that the system and the environment share identical properties, such as temperature, pressure or chemical concentration: "We express this by saying that there are no net fluxes across the system. This does not imply that equilibrium is a state of complete rigidity. Rather, it should be understood in a dynamical sense" (p. 55). Nonequilibrium is associated with non-vanishing fluxes between system and environment. Therefore, systems in nonequilibrium demonstrate differences in some variables between the system and the environment.

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[2]Some objection may be raised to the use of the word "self" in self-organizing, in that its use implies a conscious process--a "self" doing the organizing. It is used by chaologists, however erroneously, to suggest that there is spontaneous organization resulting from the application of nonlinear constraints, whether internal or external.

Nonequilibrium can be transient, arising suddenly and dying out quickly, or it can be permanent. Permanent nonequilibrium depends on the maintenance of appropriate conditions or constraints.

> Because of the continuous or temporary action of a constraint, in a nonequilibrium state detailed balance will not hold. As a result, a regime of nonequilibrium becomes susceptible to change. Localized small attempts to deviate from it are not necessarily obliterated by an instantaneously developed counteraction but, rather, can be accepted and even amplified by the system, thus becoming sources of innovation and diversification. (Nicolis & Prigogine, 1989, p. 56)

Nicolis and Prigogine (1989) provide an illuminating example of nonequilibrium self-organization in the formation of Bénard cells. These are convection cells which form in liquid that is heated. In an unheated state, the liquid is at equilibrium. The molecules comprising the system move about in random fashion, colliding with other molecules and moving off in various trajectories. Everywhere within the system this homogeneous state exists. An external constraint is then applied, in this example the introduction of heat from below. (One can visualize a pan of water on the stove.) In the case of a small temperature change, the heat introduced into the system will rise through the liquid, escaping into the environment at the top. This system is no longer at equilibrium, since there is a temperature differential in various areas of the system. If the temperature remains constant, the system will stabilize around this behavior of simple thermal conduction.

If the temperature is again raised to a critical point (ΔT_c), pushing the system far from equilibrium, the fluid abruptly begins to move in concert, forming hexagonal convection cells which circulate the heated fluid from bottom to top. Interestingly, neighboring cells move in opposing directions. If the first cell moves clockwise, its neighbor moves counterclockwise, the next cell in line moves clockwise, and so on. This suggests correlation between the cells, "as if each volume element was watching the behavior of its neighbors and was taking it into account so as to play its own role adequately and to participate in the overall pattern" (Nicolis & Prigogine, 1989, p. 13).

The moment of self-organization is referred to as a phase-transition. According to Prigogine and Stengers (1984), a system becomes increasingly sensitive to changes in variables the further that system is pushed from equilibrium. "In an [unstable] state, certain fluctuations, instead of regressing, may be amplified and invade the entire system, compelling it to evolve toward a new regime that may be qualitatively quite different from the stationary states" (Prigogine & Stengers, 1984, p. 141).

Briggs and Peat (1989), addressing the principle of self-organization, view each new regime as a new organizational level: "Each level of organization produces something fundamentally new, something that is not present in the constituent elements or 'parts' of the previous level" (Briggs & Peat, 1989, p. 149). When a system self-organizes to a new level of complexity, it is creating new information, information that was not inherent in the system before it transformed (Nicolis & Prigogine, 1989; Prigogine & Stengers, 1984). This is the archetype of creativity.

Stability and Instability

A crucial, and yet seemingly paradoxical behavioral characteristic of nonlinear systems is that they can display asymptotic stability. This is the ability of a system to experience a perturbation of sufficient magnitude to knock it out of its accustomed regimen, and yet to return to the old regimen quickly. One can think of the system retaining a memory of the original state. Linear systems, wholly governed by Newtonian laws of conservation, do not have this ability. For example, consider a simple frictionless pendulum, beating regularly at a particular amplitude. If the pendulum is given an extra push, it will start oscillating at a higher amplitude, taking a bit more time to complete each swing. In other words, it has no memory of its old pattern, and will retain the new pattern until subjected to another perturbation (Nicolis & Prigogine, 1989).

In contrast, a human heart, exemplifying a nonlinear system, will damp the effects of a perturbation introduced, for example, by sudden exertion, fear, shock, illness, and so on. Despite being thrown off its normal beat, the heart retains a "memory" of its proper rhythm, and will, under ordinary circumstances, return to its normal rhythm. It is this asymptotic stability that keeps us alive in the face of changing conditions (Goldberger & West, 1987; Nicolis & Prigogine, 1989). If it were otherwise, our first frightening encounter could clearly and literally "scare us to death."

When the heart has sustained damage due to a heart attack, it may lose this all-important stability and become like the pendulum, unable to return to its accustomed behavior. In this condition, a sudden shock or exertion may start the heart beating in a new and dangerous rhythm called fibrillation, from which it has difficulty recovering. Medical personnel use electrical shocks to "defibrillate" the heart. In effect, they are introducing another shock, another perturbation, in the hope of throwing the heart out of its dangerous new rhythm and back to the old one.

Strange Attractors: The "Finger Print" of Chaotic Systems

One way to measure the complexity of a system, as stated before, is by computing the length of the algorithm needed to specify the system. For a complex, nonlinear system, such an algorithm would be infinite. Another method for determining whether a system is or is not chaotic is by uncovering the existence of strange attractors in the data produced by a system.

What are strange attractors? Attractors of any sort can be thought of as the conditions which impose constraints on the behavior of the system. Some such constraints are physical, and the simplest can be easily visualized. Some, particularly those which come into play for nonlinear systems, are a function of the interplay between the various degrees of freedom inherent in the system. These are impossible to visualize or characterize without the mathematical manipulation referred to as "phase space mapping" (Briggs & Peat, 1989; Gleick, 1987).

Currently, there are three known varieties of attractors: point, limit cycle, and strange. Point attractors are characterized as a single point to which a system settles down. Consider a marble rolling around in a bowl. If the marble is not continually pushed, it will eventually settle into the bottom of the bowl, which serves in this instance as the point attractor. The constraints that form this attractor are provided by the sides of the bowl and the force of gravity. A limit cycle attractor is one that causes a system to oscillate between two states (Gleick, 1987). An example might be provided by a population of fish alternating between two densities. One year there are lots of fish, the next year few, the third year lots of fish, and so on. The constraints here are complicated, having to do perhaps with available food, birth rates, predators, weather factors, and competing species. A strange attractor is one which causes the system to behave chaotically. Using the fish example, if the population density never showed a pattern, there is a likelihood that the attractor is strange.

Basins of Attraction

Attractors also have basins of attraction, which are those sets of points from which a system will settle into a particular attractor (Freeman, 1991; Gleick, 1987). For the marble in the bowl, the entire bowl serves as the basin of attraction, because a marble placed anywhere within the bowl will settle to the bottom.

A system with two point attractors will have two basins of attraction. For example, a marble may be rolled down a slope towards two valleys, forming the branches of a "Y", and separated by a mounded ridge. The marble will end up in one or the other of the valleys. The choice it makes depends in an extremely sensitive fashion upon its exact trajectory. If, instead of rolling the marble down the slope leading to the valleys, it is placed in various positions throughout the entire system, the subsequent movement of the marble will reveal the basins of attraction. There will be a large area from which the marble will settle in the left valley, and an equally large area from which it will move to the right. There will also be an area, mostly on the ridge-line between the valleys, from which it proves impossible to predict whether the marble will move right or left. In fact, careful mapping at increasingly higher powers of magnification will reveal that the border between the basins of attraction is fractal.

Fractals are a physical characteristic of chaotic systems. In the words of Briggs and Peat (1989), "Wherever chaos, turbulence, and disorder are found, fractal geometry is at play" (p. 105). In a mathematical sense, these are structures which possess a dimension that cannot be expressed as a whole integer. In other words, a fractal with a dimension 2.45 would have characteristics greater than two-dimensional objects, but less than three-dimensional objects. A Menger sponge, the mathematically generated solid-looking lattice which has infinite surface area, yet zero volume, is such a fractal. It is more than a plane, as evidenced by its infinite surface, yet less than a cube, having no volume (Gleick, 1987).

One can think of fractals achieving this interdimensional character by their infinite irregularity. A widely used example of naturally existing fractals is that of a coastline. Viewed from a satellite in orbit, a coastline appears complex and irregular. Viewed at closer range, say from a bluff overlooking the sea, the irregularity persists. Closer inspection of a particular cliff will reveal irregularity, as will inspection of a particular protuberance from that cliff, and so on, down to the irregularity of the sand particles embedded in the cliff. In mathematically generated fractals, such as the Mandelbrot set, the complexity and irregularity are evidenced regardless of the level at which it is viewed. The complexity never melts into simplicity (Gleick, 1987). Thus inspection of fractals yields greater detail when inspected at higher magnification, yet preserves a resemblance to the larger scale. This characteristic of fractals is called scaling (West & Goldberger, 1987).

When the border between two basins of attraction is fractal, one can, in principle, infinitely increase the power of magnification used to determine the various points from which the marble is set rolling and never achieve predictability. Thus this fractal border between the basins of attraction provides a physical manifestation of the sensitive dependence on initial conditions mentioned earlier.

Phase Space Maps

More complicated attractors are not easy to think about in terms of physical images. Visualization of the behavior of the system requires the device of a phase space map. According to Gleick (1987):

> In phase space the complete state of knowledge about a dynamical system at a single instant in time collapses to a point. That point is the dynamical system--at that instant. At the next instant, though, the system will have changed, ever so slightly, and so the point moves. The history of the system time can be charted by the moving point, tracing its orbit through phase space with the passage of time. (p. 134)

Each variable within a system represents a degree of freedom, and necessitates another dimension added to the phase space to represent the state of that variable at each instant. Phase space incorporating more than three dimensions is impossible for most humans to visualize, and it is this that makes strange attractors so difficult to define in physical terms. However, there is a method that mathematicians use to collapse the many dimensions necessary to define the state of a complex system into fewer dimensions, which can be more easily understood (Gleick, 1987). When this is done, and the behavior of a system is graphed, the resulting picture defines the complexity of the attractor.

The portrait of a strange attractor provided by phase space mapping has several characteristics which immediately identify it as different from simpler attractors and from completely random motion. A strange attractor never settles down into a single, unmoving point. The behavior of a system under the influence of a strange attractor does trace an area within phase space out of which it does not stray. However, within this area, the trajectory lines never cross and never repeat. This means that the system does not exactly repeat its behavior--ever. If a cross section is taken of the pattern the chaotic system is creating, a section called a Poincaré section, it reveals that the pattern is fractal in dimension, thus allowing the infinitely long orbit of the chaotic system to inhabit a finite area in phase space.

A measurement of the dimensionality of a Poincaré section yields information about the relative complexity of a system's behavior (Röschke & Aldenhoff, 1992). For example, a measured dimension of 8.45 would indicate a more complex activity influenced by more independent variables than a system yielding a Poincaré section with a dimension measured at 5.72.

In short, the system constrained by these strange attractors differs from those systems having no such constraints. There is a pattern revealed by the phase space maps associated with strange attractors. It is not the haphazard collection of points that would be created by randomness. The very existence of this pattern attests to the order underlying what we view as chaotic behavior.

Summary

The purpose of this chapter has been to introduce the concepts that researchers in many disciplines identify as defining characteristics of chaotic systems. The remainder of this dissertation will focus on the relationship between chaotic dynamics and human creativity. Nowhere is there a system more complex, at times more perplexing, than the human system. Whether viewed at the scale of individual neurons, the complete brain, an entire individual, the individual within a classroom, the classroom within a school, the school within society, or humanity at large, the level of complexity persists. An understanding of nonlinear dynamics is beginning to give us the tools with which to analyze the patterns within this complexity. The next chapter will look at the ability of the human brain to use chaotic dynamics to produce novelty.

CHAPTER III

SEARCHING FOR CHAOS: A NEW VIEW OF BRAIN FUNCTION

Introduction

Since the beginning of this century, neuroscientists have understood that the brain is an extremely complex system. Approaching the brain as an engineer would approach a complex machine, early researchers sought to understand the very simplest entities and processes in the brain, hoping thereby to reveal some simple, predictable mechanism that must underlie all of brain function. Much has been discovered utilizing this approach. However, the simple underlying mechanism is still elusive. Even the most elementary processes, such as the movement of ions into and out of neuronal axons, demonstrates a complexity of response that has frequently frustrated researchers.

An understanding of chaotic dynamics, although still in the developmental stage, can be profitably used to foster new insights into how the brain works. Current theories of brain function have seemed successful in explaining some aspects of sensory perception, and are beginning to shed light on some of the mechanisms underlying memory and motor control. On a neuronal level, much has been elucidated regarding how one neuron passes information on to another neuron. However, no theory of brain function has even approached how the brain can generate creative, novel, original ideas. It is this creative function which differentiates us from other animals, and it is this function which has not been addressed in theories of cognitive processing.

As an understanding of nonlinear dynamics in chaotic systems gains wider acceptance among the scientific community and comes to be utilized by neuroscientists in conjunction with emerging technologies, new insights will be gained that will revolutionize our comprehension of human brain function. With our history of educational practices and policies reflecting our understanding of human mentation, it behooves educators to grasp the insights about human brain function that an understanding of nonlinear dynamics affords.

Basic Neurophysiology

Brain research is currently pursued on either a microscopic or macroscopic level. Investigators at the microscopic level seek to elucidate the workings of single neurons, utilizing various methods to study such areas as membrane depolarization mechanisms and synaptic organization. On a macroscopic level, investigators try to understand the working of either the whole brain, or discrete areas of the brain, either through stimulation/response paradigms, lesions studies, or computer modeling. The following information was abstracted from several sources, among them Churchland (1986), Freeman (1991), Kuffler, Nicholls, and Martin (1984), and Shepherd (1990).

Microscopic Neurophysiology

On the microscopic level, individual nerve cells, called neurons, look something like trees or bushes. The branches are called dendrites. These attach to the cell body, in which the normal cell maintenance processes take place. Exiting the cell body, the axon looks much like a tree trunk, and ends in another few branches that resemble roots. Neurons continuously receive electrochemical impulses, either from sensory receptors such as those in the eyes or skin, or from other neurons (sometimes thousands of other neurons). The site at which this communication between cells occurs is called the synapse. Although synapses do exist directly on cell bodies, the vast majority of incoming synaptic sites are on the dendrites.

Dendritic responses to incoming impulses are either excitatory, which encourage the cell to fire off an impulse to the next neuron, or they are inhibitory, telling the cell not to fire. All of the incoming pulses travel down the dendrites to the cell body and on to a region called the trigger zone, located at the head of the output axon. At the trigger zone, the cell adds up the excitatory impulses, subtracts the inhibitory ones, and fires off an impulse if the sum is over a particular threshold.

Macroscopic Neurophysiology

The brain as a whole contains many different structures responsible for the different levels of function, from those which keep us alive to those which allow us to ride bicycles and write novels. The concern in this study is with the cortex, the outermost layer of brain tissue in which occurs the "highest" level of brain activity. The following account pertains to cortical structure.

On a macroscopic level, cortical neurons, through their synaptic linkages, form densely interwoven and interacting nets. While the entire cortex is made up of these nets, which presumably all act in a similar fashion, discrete areas of the brain are responsible for particular processes. For example, the olfactory cortex plays a significant, though not exclusive, part in the perception of smell, the visual cortex responds to retinal input, and the motor cortex plays a part in initiating and coordinating movement.

How these nets of interconnected neurons process information, initiate responses, and store information is the primary question neuroscientists seek to answer. Since the invention of the serial computer, much effort has been expended in trying to find brain structures analogous to computer chips. For example, memory was envisioned as being stored in a particular part of the brain.

Much investigation has been aimed at finding this storage place and modeling the processes by which memories are stored and recalled (Lashley, 1950, as quoted in Pribram, 1971, p. 26). Similarly, many researchers hypothesize and look for a central processing unit, or as Gazzaniga (1988) calls it, an "interpreter." This can be thought of as a brain within a brain, and is seen as providing the executive function. According to investigators who have adopted the computer metaphor (see, for example, Newell, Rosenbloom, & Laird, 1989), the brain processes information in a symbolic, serial, and hierarchical fashion. Input comes in from sensory receptors, is passed on to progressively higher levels of cortical processing and finally reaches the central decision making unit. Output from this central decision maker follows a similar course, in reverse.

There is a major problem with this model of cortical brain function. Temporal constraints on processing time prove that the brain cannot work in series. Computer events are measured in nanoseconds (10^{-9}), while neuronal events are measured in milliseconds (10^{-3}). Nevertheless, in 100 to 200 milliseconds, a human can perform a perceptual recognition task that would require days for a conventional computer (Churchland, 1986).

> Some purists might insist that a serial computer can, in principle, precisely simulate physical processes, including those in the brain. Any parallel computation can also be done serially. However, if one examines what is involved in such a precise simulation it is in practice impossible, certainly in real time. To effectively simulate on a huge serial computer one millisecond of the brain's operation--how every neuron functions, every synaptic vesicle or ion moves--could take thousands of years. (Pagels, 1988, p. 117)

Clearly the brain is not utilizing serial processing. Many researchers now accept that the brain, with its undeniably complex network of neurons, must be processing in parallel (Ballard, 1986; Churchland, 1986; Mesulam, 1990; Rumelhart, 1989). A system that utilizes parallel processing (simultaneous processing of both excitatory and inhibitory inputs), coupled with the highly, and in some cases redundantly interconnected neurons, is a highly nonlinear dynamic system. A more complete description of parallel processing will be provided below in connection with the literature on neural networks.

The Brain As a Chaotic System

To establish that the brain may be viewed as a chaotic system, we need to determine whether brain function demonstrates the behaviors and characteristics of such systems.

Required evidence would include proof that the brain is a dynamic, complex, and nonlinear system. Does it demonstrate chaotic dynamics through self-organization and abrupt phase transitions? Is it possible to determine whether brain function is subject to the influence of strange attractors? And finally, if the brain is a chaotic system, does the literature include any hypotheses regarding the utility of chaos in the system?

The scientific study of chaos is a relatively new field, and few researchers have tried to tackle the dynamics of a system as complex as the human brain. However, there are a few articles in the literature that directly investigate chaos in the brain. Other chaotic characteristics can be teased out of the mainstream of literature in the neurosciences and cognitive sciences.

Fractal Structure in the Human Brain

One place to begin such as investigation is by analyzing the physical structure of the system under question, in this case, the human brain. On a macroscopic level, the brain is a convoluted mass of tissue, weighing approximately three pounds, containing various structures as revealed by dissection. Microscopically, as mentioned earlier, the brain tissue is made up of an infinitely complex network of many different types of nerve cells, all of which share some general attributes. All nerve cells, or neurons, have a cell body, an axon, and an array of intricately branching dendrites, which collect input from other neurons or receptor sites. The dendrites branch in much the same manner as trees do, with larger branches giving off smaller branches, which in turn support even smaller branches, and so on (Shepherd, 1988). The branches of most cortical neurons (i.e., pyramidal cells and stellate cells) are loaded with dendritic spines. Each spine provides five to six synaptic sites for connection to other neurons (Diamond, 1988). Chaologists refer to the visual effect of this arrangement as fractal self-similarity (see Fig. 1).

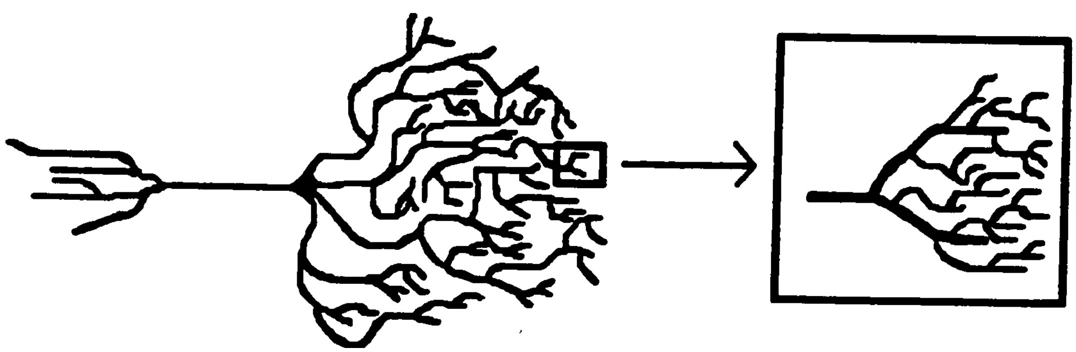

Figure 1. Pyramidal cell showing branching fractal structure. Enlarged detail demonstrates self-similarity of scale.

In their article on fractal physiology, Goldberger and West (1987) examine several physiological structures in the human body. Self-similarity and scaling are evident in the bronchial tree, intestinal mucosa, and purkinje fibers in the heart, as well as brain neurons. They note that in the bronchial tree the fractal structure facilitates gas exchange. Fractal structure in the intestinal mucosa provides more surface area, which increases efficiency of nutrient absorption. In this article, they do not speculate on why the neuron structure of the brain is fractal, but they do go into some detail on the reasons why the heart is innervated by a fractal conduction network:

> The effect of the self-similar, irregular network will be to "shatter" a cardiac impulse starting at the His bundle into myriad stimuli, cascading down the His-Purkinje system toward the myocardium. This shattering phenomenon therefore acts to de-correlate the impulses, staggering their arrival times at the Purkinje-myocardial interface. (p. 430)

Noting that a healthy heart reveals an erratic pattern, they speculate that not only is this variability a direct response to changing demands on the system, it is necessary for the flexible adaptation to changes. When something, such as an infarction, or a disease process damages the His-Purkinje system, there is a marked loss of heart rate variability, and loss therefore of the responsive flexibility to internal and external demands. This regularity signals that death is imminent (also see Gleick, 1987, pp. 280-281).

Without mentioning fractal structure, Shepherd (1990, pp. 465-466) notes that the presence of dendritic spines serves to increase the capacity of a dendrite to synapse with other neurons. In a situation where there are two neighboring synapses directly on a dendrite and both are activated simultaneously, the resulting potential is smaller than would be achieved by directly summing the potentials of each synapse. This occurs because the electrical conductances interact to reduce synaptic efficacy. As distance increases between synapses, interference decreases.

Shepherd believes that this is the reason dendrites develop a widely branching structure. The development of dendritic spines provides an additional solution to this problem. The thin stalk of the spine, upon which the synaptic head is perched, interposes a high internal resistance between synapses. The resulting fractal structure, with its self-similarity of structure and function, thus serves to increase the connectivity within brain neural networks. The result of this increased connectivity will be addressed next.

Nonlinearity and Feedback

Nonlinearity is evident on all levels of neural organization. The simplest explanation of how neurons receive and send messages to other neurons is that they receive chemical messages in the form of neurotransmitters, which trigger electrochemical waves that move down the dendrites, through the cell body, and out the axon. At the end of the axon are synaptic boutons which receive the electrochemical charge and release a neurotransmitter into the synaptic cleft shared with another neuron (Shepherd, 1988). A simple analogy is the electrical current generated when one flips a light switch and the lamp across the room lights up.

Closer examination of the propagation of this electrochemical impulse reveals that the processes involved are more complex than suggested by the light switch analogy, involving many fluctuating variables and utilizing a high level of feedback (Kuffler et al., 1984; Shepherd, 1990; Stevens, 1979). For example, the electrical impulse, or action potential, arises from the difference in electrical potential across the cell membrane of the neuron. This is caused by the balance of chemical ions inside and outside the cell. The cell membrane is penetrated by myriads of ion channels, through which the potassium and sodium, calcium and chloride ions pass. These channels differ as to which ions they will admit. The proteins forming these open and close in response to voltage changes (caused by ionic concentration) or the binding of a neurotransmitter molecule to a receptor. Ionic concentration in turn depends on how long the gates are open, and this in turn is determined by a host of electrochemical factors, including the ionic concentrations resulting from the gate being opened. This is an example of feedback, in which the output of a process is recycled and joins other factors affecting input. Such feedback processes give rise to nonlinearity in systems, and are a most significant factor in chaotic dynamics (Gleick, 1987; Pagels, 1988).

On the synaptic level, close spacing of synapses, as discussed above, leads to a nonlinear decrease in the combined action potentials. "This means that synaptic interactions are much more dynamic than is usually recognized; they have the capacity to make nonlinear contributions to the functional operations of synaptic circuits" (Shepherd, 1990, p. 467).

Feedback at the synaptic level is demonstrated by Hebb's rule, a widely accepted proposition. Hebb's rule states that synapses between neurons that fire together become stronger, and weaker when the firing of one does not accompany the firing of the other. The strengthening of the synapse is thought to occur through the ability of synaptic sites, in response to continued stimulation, to produce additional dendritic spines. Such additional spines would serve to increase the number of post-synaptic potentials, thus adding to the "weight" of the influence of transmission from that synapse (Freeman, 1991; Penrose, 1989; Shepherd, 1990). According to Shepherd (1990), "simulations have shown that when synapses of this general type are embedded in the appropriate type of network, interesting learning and self-organizational properties emerge" (p. 374).

Computer Neural Networks

As stated above, nonlinearity in the brain is not confined to the level of individual neurons, but is evident in the higher levels of organization. Unfortunately, current technology allows only the most crude indications of how brain networks function. However, there are researchers who are attempting to simulate brain function by means of computer neural networks. Findings from this field are beginning to shed light on network dynamics.

Neural networks are computers that utilize parallel processing, as opposed to the serial processing of "normal" digital computers. Unlike digital computers, which can respond only to programs, neural nets are capable of learning by experience. There are many researchers designing neural nets, and each uses a different design, so the nets all work differently.

Of most interest here are those nets designed according to neurobiological constraints. These neural nets utilize three components: neurodes, which act something like neurons; interconnects, which are like axons; and synapses, the junction between the interconnect and the neurode. As in the nervous system, neurodes accept input from a large number of other neurodes, process these inputs and generate an outgoing signal to other neurodes via the interconnects. The synapses, like biological synapses, are unidirectional. Depending on the particular neural net, these synapses may be fixed or plastic and can be assigned varying weights, which determine the power of their excitatory (a positive weighting) or inhibitory (a negative weighting) influence on the next neurode (Caudill & Butler, 1990).

The most sophisticated networks use at least three layers of neurodes, with the middle layer (referred to as "hidden") consisting of neurodes that are interconnected with each other. This configuration allows for the utilization of feedback, which is introduced into these systems via synapses that operate according to Hebb's rule. The introduction of feedback makes these systems nonlinear. The strengthening of synapses that fire together is accomplished by increasing the weights assigned to those synapses.

The ability of these networks to learn has convinced some investigators that neural nets (and probably human brains) store memories in the connections between cells, rather than in the cells themselves (Ritter, 1990; Rumelhart, 1989). This is a difficult concept to convey in a small space. Imagine, for example, that you wanted the network (or a child) to learn the letter "a". Every time "a" is presented, it causes a particular set of neurodes to fire, and each time they do, the synapses between them are strengthened. To the network, "a" now means the firing of a particular constellation of neurodes. The memory is not "in" any particular neurode; rather it is in the connections between neurodes. Information that resides in the state of a network of neurons is referred to as being "distributed."

Biological Neural Networks

In an article examining brain architecture, Mesulam (1990) proposes that large-scale parallel distributed processing networks are crucial to the processes involved in human language and memory. Mesulam's model, based on lesion studies in humans and monkeys, indicates that:

> . . . each site within association cortex belongs to several intersecting networks so that an individual lesion, even when confined to a single cytoarchitectonic field, is likely to yield multiple deficits. . . . Conversely, some lesions may remain behaviorally silent

> under certain conditions because alternative parallel channels may become available. (Mesulam, 1990, p. 602)

This model is supported by common clinical observations that (a) lesions in different parts of the brain can have the same overall affect on behavior, and (b) single lesions may lead either to partial or multiple behavioral deficits. Further support is supplied by brain mapping studies and PET (Positron Emission Tomography) studies that detect multiple areas of brain activity in response to individual complex behaviors (Pardo, Fox, & Raichle, 1991; Reiman, Fusselman, Fox, & Raichle, 1989).

Comparing the brain to computer neural networks, Freeman (1991) says that:

> . . . both rely on parallel, distributed processes among highly interconnected units in interacting networks to produce behavior; both emphasize a self-organized or bottom-up, rather than a rule-driven or top-down, explanatory approach; and both rely heavily on organized feedback among components within the system. (p. 171)

He goes on to state, however, that the brain differs from neural networks in that the collective dynamic behavior of neurons is determined by "dense local feedback" which encourages chaotic dynamics. According to Freeman (1991), the addition of a little chaos in computer neural networks might allow them to function in a truly human manner.

Chaotic Dynamics in the Brain

Thus far, the literature reviewed has attested to the presence of fractal structure in neurons and the nonlinearity inherent in neuronal and computer simulated network functioning. While dynamic nonlinear systems do, from time to time, exhibit chaotic behavior, none of these articles or books sheds much light on the chaotic dimensions of brain behavior. However, there are a few articles that provide evidence not only that chaos exists in the brain, but that it is fundamental to the way the cortex works. If these theories continue to be supported by experimental evidence, researchers will have to reevaluate the role of disorder in the propagation of order.

Walter Freeman has worked for thirty years studying the olfactory bulb and olfactory cortex in an effort to determine the mechanisms behind the perception of odor. He and his colleagues set out to investigate the physical form in which sensory information is registered in the olfactory bulb. The answer they found was unexpected. Information is registered by means of "a spatial pattern of chaotic activity covering the entire olfactory bulb, involving equally all the neurons in it, and existing as a carrier wave or wave packet for a few tens of milliseconds" (Skarda & Freeman, 1987, p. 184). Freeman says their results:

> . . . took us so far outside the range of our previous expectations that we had no physiological metaphors with which to pin them down, and we had to draw on some new and fascinating fields of mathematics and physics in order to understand their implications. (Skarda & Freeman, 1987, p. 162)

The animal portion of these investigations utilized rabbits that had been conditioned to recognize various odors, and to respond in a particular fashion to a target odor. Skarda and Freeman (1987) permanently implanted 60 to 64 electrodes in the left lateral olfactory bulb surface of each rabbit. The rabbits were then given the task of discriminating the learned odor from another odor. (Their behavioral response served as evidence that they were responding correctly.) Electroencephalograms (EEGs) were recorded from the bulbar electrodes during this task.

Freeman found that, when the animal inhaled, the EEG tracing would show a brief burst of high frequency, high amplitude activity. He then determined the dominant amplitude of the tracing from each electrode and mapped these on a coordinate plane representing the 64 electrodes. The resulting configuration resembled a topographical map. Findings showed that particular odors elicited distinctive mappings, which did not change between trials as long as the training was not altered. If the rabbit was then taught to discriminate a new odor, and was then tested again with the old odor, the map elicited was somewhat changed. The new map would persist until training was again altered.

This finding convinced Freeman and his colleagues that information is distributed throughout the bulb, rather than being resident in a single neuron, as had been previously postulated. Having demonstrated the distributed pattern of information, he went on to study the EEGs themselves.

Anyone who looks at an EEG tracing is impressed by its irregular pattern, punctuated by nonperiodic spikes, bursts of activity, and long, slow waves. Experiments showed Freeman that deep anesthesia, at near lethal levels, could suppress the irregular EEG pattern. Similarly, cortical cells that are surgically isolated from the rest of the brain while blood supply is maintained also show "silence" on EEG. These findings indicate that EEG irregularity is a very robust phenomenon, and under natural conditions does not cease until the brain is dead.

Freeman used a computer to create phase space maps of the EEG tracings generated by his rabbits (Skarda & Freeman, 1987). As mentioned in Chapter II, such maps are a graphed, three-dimensional representation of a system's behavior over time, and can reveal the attractors which are characteristic of the system's behavior. An attractor, as also discussed in Chapter II, is the behavior a system settles into while held under the influence of a particular input. Sometimes attractors are visualized as basins of attraction in which the attractor is the bottom of an energy basin, towards which the behavior of the system will fall.

> Imagine a hilly landscape surrounding a valley. Smooth round rocks will roll down the hills to the bottom of the valley. It doesn't much matter where the rocks start or how fast they're rolling, all eventually end at the bottom of the valley. In place of the hills and valleys of a real landscape substitute hills and valleys of energy. Systems in nature are attracted to energy valleys and move away from energy hill. (Briggs & Peat, 1989, p. 36)

What is exciting about Freeman's phase space maps is that they reveal strange attractors. As mentioned earlier, such attractors are typically characteristic of chaotic systems, and differ from their simpler cousins in that, when drawn as an orbit in phase space, a system defined by a strange attractor is of fractal dimension (Babloyantz & Destexhe, 1986). In addition, the path of these attractors through phase space never repeats itself (Gleick, 1987, p. 139). The main feature of a strange attractor is that it is sensitive to initial conditions. Freeman found that the EEG tracings recorded while the rabbits sniffed the target odor showed, as previously discussed, a definite burst of high amplitude, high frequency activity (Skarda & Freeman, 1987). Computer generated phase space maps of this burst activity yielded strange attractors which demonstrated a higher level of organization than did the attractor generated when the rabbit sniffed just air. From this evidence, coupled with what is generally known about brain and neuronal function, Freeman postulates that the irregularity seen on EEG tracings reflects the fundamental chaotic behavior of the brain.

The presence of these strange attractors has caused Freeman and his colleagues to propose a new theory of the way that memories are stored in the brain. He agrees with the connectionist stance that memories are stored, via synapses that are modified according to Hebb's rule, in the connections between neurons, and that the stimulation of any part of such an assembly causes the whole to fire. He postulates that each pattern of connections that the brain creates becomes a basin of attraction (Skarda & Freeman, 1987). When an animal inhales a recognized scent, thus stimulating a cell assembly to fire, the state of the olfactory cortex jumps from the background low-energy chaotic state to a high-energy state. It experiences a phase transition. When the animal is not inhaling (and therefore is not smelling anything), all attractors are latent (Skarda & Freeman, 1987).

This work by Skarda and Freeman (1987) is supported by the work of Babloyantz and colleagues (Babloyantz & Destexhe, 1986; Babloyantz & Salazar, 1985). Babloyantz and Salazar (1985) report eliciting strange attractors from the EEG tracings recorded from humans in sleep stages 2 (light sleep) and 4 (deep sleep). They note that the attractors for stage 2 have a higher fractal dimension than those in stage 4. They suggest that this decreasing dimension implies that the dynamics become more coherent during deep sleep, i.e., less chaotic. Although they were unable to find strange attractors in the EEG tracings of humans experiencing REM sleep or an awake/alert state, they suggest that this failure may reflect the need for a much longer time series in view of the greater number of variables required to define the behavior of the system.

Babloyantz and Destexhe (1986) use the same experimental regimen to study the EEG tracings of humans experiencing petit mal seizures. Examination of these tracings shows a great deal of coherence in the wave forms, and attractors of exceedingly low (yet still fractal) dimension. This means that brain activity during seizures is chaotic, but just barely. They suggest that seizures cause disfunction because the brain is driven (by a variety of possible agents) towards stable periodic motion, similar to a heart experiencing fibrillation.

In other words, during a seizure, the brain may lose asymptotic stability with its associated flexibility of response and becomes like the frictionless pendulum discussed in Chapter II, unable to "remember" its previous pattern of activity. "In such states, information processing would be impossible and recovery would be extremely difficult. However, the brain manages to remain on a chaotic attractor, although one of a very low dimensionality, in order to process reflex activities" (Babloyantz & Destexhe, 1986, p. 3517). In closing, they note that the presence of strange attractors in normal and pathological conditions indicates the presence of chaotic dynamics in the brain. Additionally, they propose that "chaotic dynamics increase the resonance capacity of the brain" resulting in "a great sensitivity to the initial conditions, and, thus, an extremely rich response to external input" (p. 3517).

In summary, Babloyantz, along with Salazar and Destexhe, have found chaotic dynamics in sleep and seizure activity (Babloyantz & Destexhe, 1986; Babloyantz & Salazar, 1985). Freeman (1991) has found it in the olfactory cortex, and is currently pursuing similar studies of the visual and auditory systems. He believes chaotic dynamics are fundamental to cortical functioning (Freeman, 1991). In addition, Freeman's demonstration of the robust character of EEG irregularity seems to indicate that chaos and chaotic fluctuations are fundamental to brain function. He suggests that possibly the role that chaos plays in the brain is one that allows easy and immediate access to all possible attractors latent in the brain. This would obviate the need to search through files of stored memories. Instead, chaotic fluctuations, keeping the system at a far-from-equilibrium state, allow the system to have instant access to any attractor in its repertoire. The choice depends, with exquisite sensitivity, on a host of tiny variables, both within the system itself, and within its context.

Chaotic Brain Dynamics and Creativity

The purpose of the foregoing discussion was to demonstrate through the literature that the brain displays the characteristics of a nonlinear dynamic system. Its highly complex structure simultaneously and instantaneously processes a multitude of incoming stimuli and sends thousands of outgoing neuronal impulses. As a nonlinear dynamic system, it is susceptible to dynamic chaotic fluctuations and is exquisitely sensitive to changes in variables. How does this nonlinearity shed light on human creativity? Does this account for the both the celebrated "Ah ha!" phenomenon and the long-term creative productivity of eminent adults? Does it explain the generation of novelty in the system?

Freeman (1991) would say that it is in the dynamics of nonlinear systems that the source for novelty exists. Although he has worked exclusively with the sensory systems in the brain, Freeman does speculate that "chaos underlies the ability of the brain to respond flexibly to the outside world and to generate novel activity patterns, including those that are experienced as fresh ideas (p. 78). Nicolis and Prigogine (1989) believe that chaotic dynamics are the information-creating force in nature: "The instability of motion associated with chaos allows the system to explore its state space continuously, thereby creating information and complexity" (p. 192). In their paper, Crutchfield et al. (1986) write: "Innate creativity may have an underlying chaotic process that selectively amplifies small fluctuations and molds them into macroscopic coherent mental states that are experienced as thoughts" (p. 57). Davies (1988) would agree: "It is now recognized that, quite generally, systems driven far from equilibrium tend to undergo abrupt spontaneous changes in behavior. They may start to behave erratically, or to organize themselves into new, and unexpected forms" (p. 83).

How might a chaotic model for creativity look? We know that a nonlinear system driven far from equilibrium is exquisitely sensitive to changes in variables, and that under the influence of such a change, the system can abruptly (and discontinuously) jump from one level of organization or basin of attraction to another. Freeman (1991) postulates that, in addition to attractors that represent previous knowledge and experience, there exists a "chaotic well" that provides escape from all established attractors and allows one to perceive the thought or perception as novel (Skarda & Freeman, 1987, p. 168).

If one translates this into human terms, one can envision the creator-to-be in a far-from-equilibrium state, due to some form of arousal such as excitement, frustration, concentration, chocolate-high, and so on. In this state, the creator's cortex is more than usually sensitive to the nuances of thought and experience. At such a time, seemingly trivial events or perceptions can cause the jump from one phase state to another. Archimedes stepping into his bath is a prime (and classic) example. This explanation for the creative event will be explored in detail in the next chapter.

CHAPTER IV

WHERE CHAOTIC DYNAMICS AND CREATIVITY MEET

Introduction

Chapter III was devoted to demonstrating that the human brain can be viewed as a nonlinear dynamic system subject to chaotic dynamics. It is a highly complex structure heavily dependent on feedback which simultaneously and nearly instantaneously processes a multitude of incoming stimuli and sends thousands of outgoing neuronal impulses. Also discussed was the ability of nonlinear systems such as the brain to generate novelty and to self-organize to a higher level of order or complexity.

The question now becomes whether an understanding of chaotic dynamics has explanatory power at higher levels of description than brain function. Can, for example, currently existing theories of creativity be re-framed from the perspective afforded by chaotic dynamics? Can chaotic dynamics help to elucidate the importance of various environmental, hereditary, and personality factors in influencing creative ability? Can such dynamics begin to offer an explanation for why young children demonstrate creative behaviors, but most adults do not? Do chaotic dynamics provide any clues about how to nurture creativity?

Chaotic Dynamics and Human Creativity

To begin to answer these questions, a possible scenario for human creative thought based upon chaotic dynamics must first be proposed. If nonlinear dynamic systems are capable of generating novelty under far-from-equilibrium conditions (see Chapter II), then it seems reasonable to suggest that these dynamics may underlie human creativity, provided human beings can legitimately be viewed as nonlinear dynamic systems.

Few would argue with the statement that each individual is a complex, highly integrated and interrelated collection of systems, which somewhat arbitrarily can be labeled as the intellectual, emotional, intuitive, and physical systems (Clark, 1988; Jung, 1971). Each of these is comprised in turn of subsystems which are closely interrelated through various direct routes and through extensive feedback mechanisms. Thus, hormones, part of the physical system, impact heavily on emotion. Emotional states in turn affect our ability to be rational, and our ability to intuit. They also feed back into the hormonal balance, which affects other physical systems. In effect, not only the brain can be viewed as a nonlinear system, but also the entire individual.

According to Prigogine and his colleagues (Nicolis & Prigogine, 1989; Prigogine & Stengers, 1984), complex nonlinear systems that are open to the environment approach chaos by being driven far from equilibrium. As such a system diverges further and further from an equilibrium state, it becomes ever more sensitive to changes in variables, until suddenly and spontaneously some fluctuation, some change in a parameter, induces it to self-organize into a new level of complexity or organization. The moment of this self-organization cannot be predicted in advance, nor can the state of the system after self-organization be predicted.

For a human being, equilibrium can be thought of as representing a state in which everything encountered is understood, and responses become automatic, requiring little or no thinking. Such a state would include no data or ideas that challenge understanding, and no external constraints that compromise the status quo. Nonequilibrium then is represented by any state in which new ideas, new situations, new feelings demand responses that are not automatic, that require some thought or some extraordinary action. The individual must assimilate the new data or the new insights into the old patterns, thereby changing the old patterns to some degree. Piaget refers to this phenomena as "reequilibration" (Piaget, 1977).

One can think of the degree of adjustment required as a measure of how far from equilibrium the system has been pushed. Individuals are different, and a situation which pushes one far from equilibrium hardly affects others. Say, for example, that substantial evidence was suddenly discovered that proved dinosaurs were warm blooded and furry. For most individuals this news would spark the same interest as an item on the back page of the local newspaper. Their equilibrium would not be seriously affected, and they would, at most, file the story away in their memory as something mildly interesting. For paleontologists, on the other hand, such news would knock them distinctly away from equilibrium. Within the circle of paleontologists some would respond to the news by reformulating their theories in light of the new evidence. They would endeavor to create new theories and perhaps thereby solve some long-standing questions, such as why dinosaurs suddenly all died out. Others would respond by refusing to discard the old equilibrium, vociferously defending their own life's work and attacking the validity of the new evidence and the professional abilities of the scientists who made the discovery.

In terms of chaotic dynamics, those paleontologists who are willing to entertain new theories in light of new findings are allowing themselves to exist for a while at a far-from-equilibrium state. They are deferring closure and suspending final judgment. They are displaying a greater tolerance for ambiguity. In this state, they are more sensitive to changes in variables, to nuances. They are perhaps more open to metaphorical thinking. They become ripe for some chance occurrence suddenly to reorder their thinking, much as Newton watched an apple fall to earth and saw a correspondence of this action to the orbiting of planets around the sun. In terms of chaotic dynamics, the chance occurrence, the perception of a new nuance precipitates an abrupt self-organization to a new level, and a new idea is generated.

The question underlying work in the area of creativity is: What differentiates the creator from the noncreator? Why do some paleontologists use new data as an opportunity to create new theories while others insist there must be some error? Why do most people enjoy flowers simply as flowers while poets see them as metaphors for love, for betrayal, for death? Why does a Robert Gates, president of Microsoft, unmotivated student and high-school drop out, become one of our most famous, creative, and successful software programmers?

Not surprisingly, there has been much research aimed at trying to define the characteristics that make an individual creative. In his concluding address to the Ninth World Conference on Gifted and Talented Children, Joseph Renzulli (1991) spoke of the "missing ingredient" that we have yet to identify in order to perfect the recipe for creative individuals. At the same time, he was admitting failure. We currently do not know this missing factor. If the perspective afforded by chaotic dynamics is valid, we will never discover the missing factor. Such research represents an attempt to predict the dynamics of an entire system based only on initial conditions. While initial conditions can exert crucial influences on a system, the nonlinear sensitivity of the system, particularly when pushed far-from-equilibrium, precludes the ability of anyone to predict a priori which conditions will prove most critical.

From a chaotic perspective, a more fruitful line of inquiry involves understanding the constraints (either external or internal) upon the human individual which either favor or inhibit the system's movement away from equilibrium. Re-framed in this manner, current research on creativity yields much information.

External Constraints

In a system as open to and interrelated with the environment as the human system is, the division of constraints into external and internal is somewhat arbitrary. The effects of external constraints can be, and often are, internalized by the individual. However, factors such as historical period and cultural expectations are imposed from the outside, whereas factors such as innate personality and desires are generated within, even though they may be influenced by external factors.

External constraints in the sense used here are the environmental factors which either encourage an individual to diverge from standard modes of thought and expression, or discourage any movement away from the status quo. In this respect, family, societal, and cultural expectations are strong environmental constraints. Similarly, historical setting as expressed in political, financial, and aesthetic expectations, can either encourage or discourage creative behavior. The following sections will provide a sampling of the literature concerning these environment constraints.

Family Influence

Dacey (1989) studied the families of adolescents who were judged to be creative. Using an interview methodology, factors such as parenting styles, home environment, housing, childhood trauma, schooling, and the presence or absence of reinforcement for creativity at an early age were all studied. The author reported that on all parameters the families of creative adolescents demonstrated a creative lifestyle. Humor was important to these families. Parents were pleased to have creative offspring and tended to reinforce and facilitate creative behavior. Houses were not stereotypical. Parents of these children did not "rely on rigid sets of rules to control their child's behavior. Instead, by modelling and family discussions, they espouse a well-defined set of values" (Dacey, 1989, p. 267).

This study provides an interesting glimpse into the family life of some creative individuals. Unfortunately the author chose not to include the particular results of his tests and interviews. The impression one is left with is that all families tested demonstrated the same traits. Such an impression suggests that one has only to duplicate the family environment outlined in this article to ensure the production of a creative offspring.

Family influences can also obstruct the creative expression of individuals. This was demonstrated by Gedo's (1990) study of the families of his creative psychiatric patients. The author found that all of his creative patients shared a childhood history of having shown some evidence of unusual creative ability. Many of these patients experienced an inability of their early caretakers to respond to their special endowments with support and encouragement. "In many cases, the families of these gifted children were not just uninterested in the potential of their offspring; often, they were actively hostile" (Gedo, 1990, p. 38). As adults, these children demonstrated a degree of psychopathology requiring professional intervention.

Unwilling to leave us with an oversimplified message, the author then examined family and social influences on the lives of famous artists and musicians. The resulting array of influential configurations does not lend itself to simple categorization. For example, Mozart was nurtured by a family that expected he would become a musician. However, according to Gedo (1990), he suffered a great deal of bitterness stemming from his parents' "proprietary attitude about his creativity" (p. 40). This contributed to the disordered behavior depicted in the film Amadeus.

Gender Roles

Ravenna Helson (1990) studied female creativity in light of familial and environmental influences, thereby underscoring the difficulty that creative women in our culture experience:

> As I see it, the external bias of the environment toward restricting women's power and the internal influence of women's problems with dependence (being in the power of others)--these interact [with] and reinforce each other. One reason the girl remains dependent on her parents is that the social world doesn't put pressure on her to become an independent, achieving person. And when the environment does offer the young woman an opportunity for creative work, she may not have the independence and confidence to take advantage of it--perhaps she can't manage the tension or she is afraid of the risk or responsibility. So her record doesn't look good, she is unsure of herself, and the environmental agents are confirmed in their views. (p. 49)

Helson goes on to enumerate factors which seem to contribute to creativity in women. For example, she states that if a girl is singled out as special by achievement-oriented parents, she is more likely to become creative. This belief was supported in her study of creative female mathematicians in which she found that most of the women studied lacked brothers, and so became the recipients of parental interest.

Inherited power, such as that wielded by monarchs, is another factor which Helson (1990) cites as supportive of creative behavior. Elizabeth Tudor, probably one of history's most politically creative rulers, provides a grand example. Similarly, female creative expression is supported when it assumes a form, such as that of a ballerina or actress, that is deemed socially acceptable and necessary. Women also do well in areas such as literature where there is "a minimum of institutional credentialing, status, and bureaucracy" (Helson, 1990, p. 49). She concludes that, due to social expectations, few women see themselves as creative individuals.

Helson's findings are supported by the experience of Harriet Hosmer (cited in Ross, 1992), a nineteenth-century American sculptor. On the subject of marriage, she once wrote:

> For a man, the mix of marriage and a career in art is all well enough, but for a woman on whom matrimonial duties and cares weigh more heavily, it is a great moral wrong, I think, for she must either neglect her profession or her family. (pp. 24-25)

Clark (1988) repeatedly suggests that in order to nurture creativity in students, teachers should avoid sex role stereotyping. In terms of chaotic dynamics, Helson, Clark, and other researchers following in the same vein, have demonstrated that in this country, sex role stereotyping serves as a constraint which discourages women from diverging from socially accepted norms of behavior.

Historical Constraints

Historical constraints are defined here as covering a wide range of factors which are tied in one way or another to particular time periods in particular cultures. Included would be the "state of the art" for any particular domain, available technology, political considerations, aesthetics, finances, and a host of other variables that may either encourage an individual to risk departing from accepted modes of thought or discourage such exploration.

The Shoulders of Giants

Toward the end of his life, Sir Isaac Newton is reported to have said that he was able to accomplish so much because he stood on the "shoulders of giants." This statement attests to the cumulative nature of knowledge in the scientific arena, and the fact that, in general, individuals within a field or domain take as their legacy the accomplishments of those who have gone before. Feldman (1991a) speculates about this phenomena: "One wonders, for example, whether a mind like Einstein's in Galileo's day would have made a contribution to the existing state of knowledge about the physical world" (p. 13).

The importance of the historical milieu is equally evident in cases where individuals indulge in radical departures from current knowledge. Such creators are usually not acknowledged in their lifetime, but in retrospect are labeled as being "ahead of their time." Leonardo Da Vinci is a prime example. Creative achievement seems to require a fortuitous fit between the interests and capabilities of the creator and the time into which s(he) is born.

Technological Constraints

The state of technology with respect to a specific field also comprises constraints. A powerful example is provided by the recent discovery of recombinant DNA technology. This knowledge, and the technological advances which make gene manipulation possible, has resulted in an explosion of creative new research in a wide number of fields. Hope is being fostered that cures will be developed for genetic diseases such as cystic fibrosis. Newly developed bacteria clean up oil spills in the oceans. Dioxin in waste dumps is being devoured by new strains of fungi. A similar explosion of creative ideas in the field of astrophysics has been encouraged by satellites such as the Voyager series, and by recent advances in telescope technology. In short, technological advances can encourage creative effort by providing tools that enable researchers to study areas that previously were too far removed from the realm of possible study. The discoveries made by using such new technologies allow researchers to push back the boundaries of knowledge, far beyond yesterday's equilibrium.

Cultural Constraints

Cultural constraints, which are a function of time and place, and which can and do affect aesthetics and politics, can be either supportive or unsupportive of creative behavior. As has been amply demonstrated at various periods of our history, cultural constraints can forbid the development of new technologies or the opening of possible areas of study. For example, up until the last two centuries, the Catholic Church forbade dissection of dead human bodies. This stricture seriously hampered the efforts of those interested in medicine to understand the workings of the human body, and thus obstructed their ability to devise new and effective treatments for disorders.

Howard Gardner (1989), in his study of Chinese arts education, provides a striking example of how a cultural aesthetic in the People's Republic of China has become a political imperative which proscribes innovation:

> From an early age, Chinese parents and teachers convey to their charges clear and unambiguous ideals about what a painting should look like, how a story should be told, how an instrument should be played, a dance step executed, a calligraphic verse completed. There is one right way and many wrong ways; the right way is beautiful and should be enacted, while the wrong ways are ugly and should be spurned. (p. 264)

Gardner (1989) also makes the point that the Chinese equate beauty with morality, and that art is "expected to convey the messages of the proper socialist order and can do so only if it harbors the proper content" (p. 268). To deviate from the accepted aesthetic is risky. "Throughout the decades, modern Chinese artists who have attempted to convey a more complex moral outlook have been officially frowned upon, and some have been permanently silenced" (p. 268). Gardner does note that some Chinese artists harbor "somewhat more adventurous work" in the privacy of their own studios, but that these works cannot be displayed. They have "struck a deal with their culture: paint in a certain way, do not deviate, and you will be supported handsomely" (p. 175). Many of these artists find their way to the United States, much as Soviet artists who wished to deviate from the accepted Soviet methods and subjects strove to reach Paris, a city which historically has encouraged artistic freedom.

Financial Constraints

Financial constraints are among the most directly visible factors influencing creative production, and they, as with the other constraints, can be either supportive or unsupportive. The old adage that "he who pays the piper chooses the tune" has far-reaching validity. The case of the Chinese artists, paid by the state, provides an example of unsupportive constraints. In the West, particularly during the Renaissance, artists depended upon the support of private patrons. Frequently these patrons determined the projects that were undertaken, as exemplified by the sculptor Michelangelo being required to paint the Sistine Chapel.

An artist who failed to please his patron found himself without means of support. Presumably, some artists attracted patrons who were drawn to their particular vision, and they were thus fairly free to pursue their own projects. Undoubtedly others were not so fortunate.

In the sciences, the situation is not dissimilar today. In the "old days" of the eighteenth and nineteenth century, many scientific inquiries were pursued by amateurs such as Benjamin Franklin, whose livelihood did not depend upon their scientific explorations. They were therefore free to follow any line of investigation that took their fancy. Now, however, most scientists interested in a particular line of investigation must first secure funding to cover the costs of the study. Generally, securing funding means submitting grant proposals to various agencies who are looking for specific kinds of projects. "Most grant proposals require clearly defined research, leaving little room for discovering anything truly new. Although hypotheses can be explored and checked out, possible outcomes are already explicit in the grant application" (Rosenman, 1988). On a similar note, Thomas West (1991) describes a senior cancer researcher who is kept so busy designing studies acceptable to granting agencies and then writing the grants that there is no time to be creative:

> He suspects that there is enough information available now to fit the pieces of the puzzle together if only there were time to sit in the library and quietly think it through. But there is no money for simply sitting in the library and thinking. (p. 203)

In effect, many funding agencies want assurance up front that their outlay of funds will result in some tangibly valuable product--a cure for cancer, a remedy for ozone depletion, a guaranteed method for educating all youngsters, a cure for AIDS. They want to know in advance the outcome of a creative process. The need for such assurance essentially precludes really creative research, and those projects which are awarded funding are frequently elaborations or small variations on old themes. J. H. Humphrey (cited in Rosenman, 1988) says that an ideal grant application should read: "These are the lines along which I expect to begin my experiments, but I really hope an unforeseen observation will prompt an unexpected idea" (p. 137). Humphrey then goes on to say that only a particularly enlightened granting committee would fund such a proposal. Such an attitude on the part of granting organizations effectively cuts out much possibility for serendipitous discovery, even though such discoveries time and again have proved to be the catalyst for real scientific breakthroughs.

Risk

Daniel Rubenson (1990) has developed a psychoeconomic theory of creativity which provides an integrative explanation for the power that external constraints exert on the creative process. Fundamental to his theory is the proposition that creative potential within any individual results from a combination of initial endowment, such as genetic inheritance and "active investments in creative ability" (p. 10). The rate at which one invests in creative activity is dependent upon the cost or risk such an investment entails. If the cost is too high, i.e., the risk is too much in light of the expected benefit, then investment of "human capital" is far less likely.

Some costs are imposed by the inherent limitation of available time and resources. Scarce resources are valuable and one is inclined not to be wasteful. Rubenson (1990) notes that the creativity literature attests to the reduction in creative output experienced by those whose time is burdened by such activities as administrative duties and childrearing. According to the theory, one is not likely to neglect the duties owed one's employer in order to "waste time" on a creative exploration which cannot promise to be fruitful. To do so entails the risk of being fired.

However, if creative activity promises financial incentives and/or recognition, then such activity becomes more likely.

The Chinese artists studied by Gardner (1989) experienced a risk represented by societal and political forces which can and do punish those who deviate from the accepted forms. As Gardner notes, individuals in such circumstances are less likely to accept such a risk. Many Chinese artists intent on developing new forms leave China and come to the United States, where the risk of being different carries less cost.

As part of a study comparing professionally competent artists and scientists with artists and scientists who were critically acclaimed, Rostan (1991) questioned the subjects as to whether they enjoyed taking chances. While all four groups of subjects indicated some uneasiness with risk taking, the professionally competent scientists "verbalized a significantly greater displeasure with taking chances" associated with their primary source of income than did the other three groups (p. 252). Significantly, Rostan reports that "many of the subjects indicated that they should enjoy taking more chances in their work than they currently did" (p. 253), seeing this as necessary for further growth. Factors verbalized as inhibiting risk-taking behavior included concern for financial stability and responsibility that the scientists had assumed "for their lab and the technicians and post doctoral researchers associated with them" (p. 253).

Psychic Risk

Psychic risk is another facet in the overall picture of possible costs. Most often recognized is the risk that creative individuals run by being "different." The penalty for being different can range from having to endure teasing to complete ostracism from one's society or field of endeavor. Radical departure from established norms has at times been viewed as highly subversive and has resulted in ostracism, imprisonment, and death. Gardner (1989) speaks of a Chinese calligrapher:

> [He was] obviously a maverick; he proceeded to carve out a life, and a livelihood, along these lines. For this, and no doubt other reasons, he was condemned as a "rightist" and had gone into hiding for twenty years, often living from hand to mouth, undetected in the woods. Finally, after the fall of the Gang of Four, when he was nearly seventy, he had returned to civilization. (p. 178)

In the West, Socrates, Galileo, and Solzhenitsyn are well-known examples.

Similarly, when a creator is subjected to evaluation by outside sources, there is psychic risk. This was demonstrated in a set of studies conducted by Amabile, Goldfarb, and Brackfield (1990). They investigated the effect that evaluation expectation and surveillance had on creativity.

Findings showed that groups not expecting their creations to be evaluated produced more creative poems than did groups who expected expert evaluation. The second study, in which surveillance by an audience was added to the research design, showed that groups not being evaluated produced more creative designs. In addition, groups who were not aware they were being watched while they created collages demonstrated higher levels of creativity.

A different type of psychic risk can be experienced by those who have already invested much time and effort within a field. New directions of thought, whether entertained by veteran individuals or newcomers in the field, can threaten to devalue or even invalidate previous achievements. Rubenson and Runco (1991) postulate that such psychic risk may explain why many veterans in a field are unwilling to entertain new perspectives, but rather expend much energy defending their previous achievements. If they are right, this same mechanism would help to explain why children, who have relatively little invested in previous achievements, tend to function in a more open and creative way than adults.

From the perspective afforded by chaotic dynamics, Rubenson's concept of costs and risks are factors that tend to encourage remaining in a near-equilibrium state. Benefits, on the other hand, or perceived pay-off for creative activity, encourage exploration far from equilibrium.

Internal Constraints

Much research in the field of creativity is devoted to exploring the creative person, attempting to delineate the personality factors that differentiate creative individuals from those not so endowed. Included in this body of theory are writings on motivational aspects and the development of purpose which apparently sustain the creative individual through the early stages of preparation all the way to the finished creative product. For the purpose of this study, personality traits and their impact on motivation and purpose can be re-framed as internal constraints, factors that either encourage or discourage movement away from equilibrium.

Creative Types

There is a large body of literature which attempts to define the characteristics of creative individuals (see, for example, Arieti, 1976; Barron, 1969; Clark, 1988; MacKinnon, 1965; Maslow, 1968; Perkins, 1988; Sternberg, 1988; Torrance, 1988; Wallace & Gruber, 1989). The lists of creative characteristics rendered by these and other authors can be roughly divided into (a) personality characteristics that foster the ability to experience creative insights, and (b) those that support production of creative products. These characteristics do not necessarily occur together. Many individuals may have the ability to experience creative insights, but lack the ambition, motivation, purpose, or desire to work the insight into a form which others may then share. Great creators necessarily possess both types of characteristics.

Of the two groupings of characteristics, those that foster creative insight can easily be described as characteristics that encourage movement away from equilibrium. For example, Sternberg (1988, pp. 139-142), in his three-facet model of creativity, asserts that creative people tend to be the "legislative type," preferring to create their own rules, and do things their own way. They "prefer problems that are not prestructured or prefabricated" (p. 139). He also says they embrace a progressive style, as opposed to a conservative one. According to Sternberg, this means they like to go beyond existing rules and procedures.

Similarly, such individuals like to maximize change, prefer unfamiliarity in life and work, and seek out ambiguous situations. Sternberg also believes creative individuals tend towards being "globalists," meaning they think about the "big picture," are idea-oriented, enjoy abstract thinking, are conceptualizers, and "show an occasional or possibly frequent tendency to get lost on cloud 9" (Sternberg, 1988, p. 141). Sternberg also includes in the list of creative characteristics tolerance for ambiguity, which he calls the "sine quo non of creative performance" (p. 143). Acceptance of moderate levels of risk, lack of conventionality, independence, and flexibility are other characteristics Sternberg lists.

Maslow (1968) lists similar characteristics, such as openness to experience, spontaneity, and freedom from stereotypes. He asserts that creative individuals are attracted to that which is unknown, mysterious, and puzzling, and that they tend to defer closure on a problem.

Clark (1988) lists independence, zany sense of humor, resistance to group pressure, adaptability, and adventurousness as characteristics of creative individuals. She states they show a preference for complexity, asymmetry and open-endedness, and possess high divergent thinking abilities. She notes that creative individuals have little tolerance for boredom.

Perkins (1988) adds a propensity for "boundary fiddling" to the list of creative characteristics. He defines this as the tendency that some individuals show for challenging existing boundaries and "asking what other boundaries might be drawn" (p. 372).

For Krishnamurti (1964), creativity has its genesis in the "initiative which comes into being only where there is deep discontent" (p. 47):

> [One must] not be afraid of discontent, but give it nourishment until the spark becomes a flame and you are everlastingly discontented with everything, . . . so that you really begin to think, to discover. . . . To find out what is true you must be in revolt against the established order. (p. 47)

MacKinnon (1965) studied the personality types and creativity of a large (n=124) group of architects and correlated their creativity level to Otto Rank's taxonomy of personality types. First the creativity of each member of this population was evaluated, then they were divided into three groups: Architects I (most creative), Architects II (moderately creative), Architects III (least creative). MacKinnon subjected these three groups to a series of tests devised to ascertain whether they fit into Rank's Adapted, Conflicted, or Creative personality types.

Findings showed a strong correlation between the least creative architects and the Adapted personality. An individual of this type, according to MacKinnon, naturally conforms to social expectations. Generally seen as well adjusted, this individual's conformity allows fewer creative possibilities. Correlations were equally strong for the moderately creative architects and Rank's Conflicted personality. These types involve themselves in breaking away from socially sanctioned goals, morals, and ethical standards. They are therefore more open to creative possibility. Strong correlations also existed for the most creative architects and Rank's Creative personality. Such individuals are in harmony with themselves and feel free to express their creativity in any form which they devise. They are confident and self-accepting.

Piechowski and Colangelo (1984), building on the work of Dabrowski, look at personality differences as biologically based. They assert that creative, gifted individuals exhibit psychic overexcitability. This overexcitability can be expressed in one of five modalities: psychomotor, sensual, intellectual, imaginational, and emotional. The authors state that "as personal traits, overexcitabilities are often not valued socially, being viewed instead as nervousness, hyperactivity, neurotic temperament, excessive emotionality, and emotional intensity that most people find uncomfortable at close range" (p. 81).

Of particular note in the context of characteristics which tend to push an individual far from equilibrium are the modalities of intellectual, imaginational, and emotional overexcitabilities, although psychomotor and sensual overexcitability can certainly also serve this function. According to Piechowski and Colangelo (1984), individuals expressing intellectual overexcitability tend to be persistent in asking probing questions, are preoccupied with theoretical problems, and show independent thought. Other characteristics are "symbolic thinking, development of new concepts and striving for synthesis of knowledge" (p. 81).

Imaginational overexcitability is seen in individuals who seem to have an extremely rich association of images and impressions. They display "inventiveness, vivid and often animated visualization, use of image and metaphor in speaking and writing" (Piechowski & Colangelo, 1984, p. 81). Emotional overexcitability is associated with unusual intensity of emotional response. These individuals demonstrate "great intensity of feeling and awareness of its full range" (p. 81). Such intensity can be expressed at either end of the emotional spectrum, from extreme timidity and shyness to extreme enthusiasm.

In a study comparing indicators of overexcitability in intellectually gifted adults, gifted adolescents, and graduate students, Piechowski and Colangelo (1984) found that gifted adolescents and adults showed the same profile of intellectual, emotional, and imaginational overexcitability, and that this profile differed markedly from that of the graduate students. The authors conclude that "this constancy supports the idea of developmental potential as original equipment" (p. 87). The authors also note a high correlation within individuals between imaginational and emotional overexcitability. The other modalities show no consistent pattern of occurrence. They conclude that overexcitabilities do not represent specific areas of competence, but rather "represent the kind of endowment that feeds, nourishes, enriches, empowers and amplifies talent" (p. 87).

Piechowski and Colangelo's (1984) work may hold one key to the question of why some individuals tend to be creative and others do not. It is conceivable that psychic overexcitability may be an internal constraint which persistently pushes or entices individuals into far-from-equilibrium states.

Furthermore, the personality traits mentioned in the first part of this section, such as tolerance for ambiguity, independence, resistance to conventionality, and so forth, are easy to attribute to individuals with these psychic overexcitabilties. Such characteristics do not comprise the entire picture however. Purpose and motivation are also important factors which not only contribute to excursions far from equilibrium, but also can support the production of creative products.

Purpose

Researchers such as Feldman (1989, 1991a), Gruber (1988), Albert (1990), and Ochse (1990), who have devoted their efforts to studying the creative process of eminent creators, emphatically view creativity as the result of a lengthy process directed towards a particular goal. They speak in terms of the creative life, rather than the creative moment. They acknowledge little similarity between the processes of inspiration and those of creative productivity.

Studies of eminent creators are striking in their similarities, and yield similar descriptions of the nature of creativity. For example, Feldman (1989) defines creativity as:

> . . . the purposeful transformation of a body of knowledge, where that transformation is so significant that the body of knowledge is irrevocably changed from the way it was before. . . . This notion of creativity emphasizes high-level functioning brought to bear on specialized problems. (p. 241)

Gruber (1988) says:

> Creative people commit themselves to creative tasks. In other words, they hope to make some change in the sum of human knowledge and experience. This is a commitment of some moment, and it is a choice, for it is entirely possible to make the opposite commitment--to live in the hopes of not causing a ripple. (pp. 32-33)

Ochse (1990) postulates that the real difference between creative people and others is their motivation. Speaking of Flaubert, Ochse says:

> Flaubert's motivation to work exceeded his motivation to engage in other activities that were satisfying in themselves. He loved his work . . . probably because his work was indeed more than an end in itself. It allowed him to test himself and produce something to show that he could pass the test. (p. 138)

Albert (1990), in the process of differentiating "real world creativity" from creativity that can be tested in a laboratory says: "Real-world creativity is built upon a series of deliberate assertive efforts" (p. 4).

Gruber (1988) insists that, in the context of the creative life, momentary inspirational experiences are overemphasized. He asserts that truly creative production results only when flashes of insight are combined with "furious bursts of work, and slower processes of growth--all linked together by the common thread of purpose" (p. 41).

The ability to sustain purposeful endeavor is thus conceived as a main characteristic of high level creators. The question remains whether this characteristic can be reframed as an internal constraint, or perhaps as an "initial condition" which encourages the human system towards a far-from-equilibrium state, thus priming it for a creative leap. Such re-framing is not difficult. Human beings have the cognitive ability to imagine the future and work towards realizing some future state. Because we can imagine future states, the mental image is available in the present. This mental image joins with the montage of factors that make up the dynamic, ever-changing set of constraints. Therefore, a future goal can easily exert an influence which serves to propel the creator towards the chosen goal.

Intrinsic Motivation

In casual usage, motivation and purpose can have the same meaning. For the purposes of this discussion, purpose means the goal towards which one moves, while motivation is the energy source which one uses to pursue the goal. Current psychological theory differentiates intrinsic and extrinsic motivation (Amabile, 1990; Csikszentmihalyi & Nakamura, 1989; Deci, 1975; Lepper & Hodell, 1989; Ochse, 1990).

Simply defined, intrinsic motivation arises from such internal factors as desire, hope, enjoyment, love, and imagination. Extrinsic motivation arises when external forces, such as promises of reward or punishment, influence an individual's behavior. Studies of the effect on creative production of internal versus external motivation demonstrate that internally motivated individuals tend to be more creative than those who are externally motivated (see below). Interestingly, when seen from the perspective of chaotic dynamics, the intrinsic motivational factors seem to be those which encourage an individual to deviate from the norm, while extrinsic factors apparently function to keep an individual close to equilibrium.

Amabile (1989) proposes that an important aspect of intrinsic motivation is self-determination, and that creativity is enhanced when the creator is in the position to make choices. These assertions are based on a series of studies testing the effect of self-determination on creative production. For example, in one study, nursery school children were asked to make collages out of various offered materials. Half of the group were told which materials they could use, and half were allowed to make their own choices. The finished collages were scored for creativity by eight artists. Those made by children who were allowed free choice of materials scored higher than those of the other children. Furthermore, when all of the children were presented two weeks later with the same materials, it was noted that the group allowed to choose materials for themselves spent significantly more time with the collage materials than did individuals from the other group. In other words, denying the first group the ability to choose for themselves seemed to diminish their desire to work with these materials later, even though at the second presentation they were allowed to make their own choices (p. 59).

Amabile notes that the introduction of extrinsic factors, such as rewards or punishments, alter an individual's perception of the task. When one is focussed on either a reward or a punishment, one tends to try to minimize the risk of failure. Amabile uses a metaphorical maze to illustrate her point. The maze is constructed with one entrance and several exits. There are several possible routes through the maze, including one which is a straight-line path from the entrance.

> If you are extrinsically motivated by something outside of the task itself (such as a promised reward for finishing), the most reasonable thing for you to do is take the simplest, safest path--to follow the familiar routine, the conservative method. If, however, you are intrinsically motivated, you enjoy being in the maze, you want to explore it, and you will be able to take those dead ends in stride. Only then will you be likely to discover a new and possibly creative way out. (Amabile, 1989, p. 62)

Lepper, Greene, and Nisbett (1973) studied the effects of extrinsic reward on intrinsic interest. After establishing through observations that marking pens and paper held intrinsic interest for a group of nursery school students, the group was divided into three. Each individual was taken to a room and asked to use the markers and paper to produce a drawing. Children in one group received no rewards for this activity. Those in the second group received an unexpected reward. Members of the third group were told before they drew the pictures that their efforts would be rewarded.

All of the pictures were evaluated for overall quality by three judges who were blind to the experimental conditions experienced by each individual. Pictures drawn by children in the expected-award condition were of lower quality than those of the other groups. Additionally, after the drawings were made, the children in the expected-award condition showed "decreased interest in the drawing activity after having undertaken it in order to obtain a goal which was extrinsic to the pleasures and satisfaction of drawing in its own right" (Lepper et al., 1973, p. 135).

Deci (1975) found the same kind of negative effect when money was offered to subjects for engaging in an activity that they enjoyed.

Lepper and Hodell (1989) note that the results of a number of studies demonstrate that the offer of extrinsic rewards undermines performance, particularly "on tasks where creativity of response is the central criterion of performance" (p. 80).

The internal and external constraints discussed above by no means represent all the possible routes to the far-from-equilibrium state. Possible routes are as numerous as individual experiences. For example, possessing a burning question, one that you feel you simply must pursue, is a constraint favoring far-from-equilibrium. Deliberately choosing or being forced to adopt a new perspective draws one away from old patterns. Stressful constraints such as deadlines seem to energize some individuals and induce them to move from equilibrium. Witnessing or contemplating events which evoke strong emotions, such as love, anger, fear, or puzzlement, can also move one away from one's "normal" perspective. Meditation, drugs, chocolate, encounter groups, hot springs, sheer determination, and sleepless nights--all can be routes to far-from-equilibrium states.

Far-From-Equilibrium States

In the context of creativity, the foregoing discussion of internal and external constraints is important only insofar as such constraints encourage or discourage movement away from equilibrium. Such factors are important because, according to Nicolis and Prigogine (1988), the further from equilibrium a system moves, the more sensitive it becomes to changes in variables, and the more easily it can experience phase transition or self-organization.

This question now arises: What does it mean for an individual to be far-from-equilibrium? Can distance from equilibrium be quantified? Is there a threshold dividing business-as-usual from such a state? Does being far-from-equilibrium guarantee a creative insight?

Most obviously, far-from-equilibrium means radical deviation from equilibrium. As noted above, the word "equilibrium" is used by psychologists to mean a balance or harmony between the system and its environment. As new information is received from the environment, balance is maintained either by assimilating the new data to existing cognitive structures, or by changing cognitive structures to accommodate new data (Ginsburg & Opper, 1988). This process inexorably changes the system by changing the cognitive structures.

> Each successive level of equilibrium reaches a better form of knowledge through the addition and reorganization of cognitive elements. The quantitative and qualitative changes result in new relationships, new understandings, and the solving of certain problems, but also open up the possibility of new questions and problems, of new imbalances and disequilibria. (Ginsburg & Opper, 1988, p. 222)

This interpretation of Piaget by Ginsburg and Opper (1988) sounds remarkably similar to the chaos model: movement away from equilibrium setting the stage for self-organization to a new level of complexity or information. In fact, Piaget fully appreciated the role that disequilibrium or cognitive conflict played in creativity. In his one statement about creativity, Piaget (cited in Gallagher & Reid, 1981) proposes three conditions that foster creativity. All three can easily be interpreted as encouraging movement away from equilibrium:

> The first condition is to work alone, to ignore everybody else, and to mistrust every influence from the outside. . . . The second condition that I think is necessary is to read a great deal in other disciplines, not in one's own discipline, . . . so as to develop an interdisciplinary outlook. Reading a lot in the related and surrounding fields, but not in one's own precise field, is necessary. And a third aspect I think in my case has been that I have always had in my head an adversary--that is, a school of thought whose ideas one considers to be wrong. (Piaget, cited in Gallagher & Reid, 1981, p. 222)

Similar to Piaget's notion of the role of disequilibrium is Gruber's concept of deviation-amplifying processes (see Wallace & Gruber, 1989). In contrast to deviation-correcting systems which serve to restrict the consequences of small fluctuations from normal, deviation-amplifying systems explore and elaborate fledgling discrepancies or novelties. Gruber states that deviation-amplifying systems are necessary for creative work (Wallace & Gruber, 1989, p. 8).

Csikszentmihalyi (1990b) has identified a state of optimal experience which he has named "flow," and which, from his description, seems to encompass both the far-from-equilibrium state and the associated self-organization:

> In our studies, we found that every flow activity . . . had this in common: It provided a sense of discovery, a creative feeling of transporting the person into a new reality. It pushed the person to higher levels of performance, and led to previously undreamed-of states of consciousness. In short, it transformed the self by making it more complex. (p. 74)

According to Csikszentmihalyi (1990b), flow is usually experienced when an individual is concentrating on a challenging activity while in pursuit of some important goal. He emphasizes that an appropriate ratio must exist between the degree of challenge and the level of skills. If skills are high and the challenge is minimal, the experience will most probably be boring and flow will not be achieved. If the challenge requires far greater skills than an individual possesses, then the activity will most likely be deeply frustrating, and, again, one will not experience flow. "The best moments usually occur when a person's body or mind is stretched to its limits in a voluntary effort to accomplish something difficult and worthwhile" (p. 3).

The perceived importance of a goal also acts as a constraint on the system. Trivial goals which are easily met do not trigger a flow experience, because there is no sense of successfully meeting a difficult challenge. To illustrate this point, Csikszentmihalyi (1990b) contrasts the goals of a mountain climber (to conquer a difficult mountain without experiencing serious injury or death) with a distinctly mundane goal:

> If I set as my goal to remain alive while sitting on the living-room sofa, I also could spend days knowing that I was achieving it, just as the rock climber does. But the realization would not make me particularly happy, whereas the climber's knowledge brings exhilaration to his dangerous ascent. (p. 55)

While Csikszentmihalyi (1990b) insists on the importance of clear goals for attaining a flow experience (which may not necessarily entail creative activity), he does acknowledge that in the case of creative endeavors the goals may not be clearly set in advance. Indeed, the author suggests that lack of precise definition of goals may differentiate conventional from creative production:

> Whereas a conventional artist starts painting a canvas knowing what she wants to paint, and holds to her original intention until the work is finished, an original artist with equal technical training commences with a

> deeply felt but undefined goal in mind, keeps modifying the picture in response to the unexpected colors and shapes emerging on the canvas, and ends up with a finished work that probably will not resemble anything she started out with. (Csikszentmihalyi 1990b, p. 208)

In the beginning of this section, several questions were posed. The first--What does it mean to be far-from-equilibrium?--has been addressed. In the context of creativity, far-from-equilibrium seems to be a state characterized by stretching beyond one's customary skills or boundaries. Challenging goals and burning questions seem to provide the justification for a purposeful departure from equilibrium, and many would contend these factors are requisite for creative insight (see, for example, Csikszentmihalyi, 1990a; Feldman, 1991a; Gruber & Davis, 1988). Specifying how far from equilibrium one must diverge in order to undergo the self-organization which signals a creative insight is not easily answered.

In a very simple system, such as the one giving rise to Bénard cells (see Chapter II), it is possible to quantify the distance from equilibrium that the system must attain before it undergoes phase transition. For an individual however, it is unlikely that one can make the same determination. Even if this were possible, distance from equilibrium must change perpetually as the system experiences continuous internal and external fluctuations. Similarly, it is impossible to determine in advance the threshold between business-as-usual and creative insight, since such a threshold depends with exquisite sensitivity upon all constraints and fluctuations experienced by the system.

The Role of Chance in Creativity

The further from equilibrium a nonlinear system diverges, the more sensitive it becomes to changes in variables, becoming exquisitely sensitive at far-from-equilibrium states (Nicolis & Prigogine, 1989; Prigogine & Stengers, 1984). Because of this characteristic of nonlinear systems, chance occurrences can trigger a system to transform itself.

Many theories of creativity omit mention of chance as an important factor, probably because the reason that theories are constructed is to enable scientists to make accurate predictions about future events or behavior. Chance events limit or abolish this ability. However, as Tannenbaum (1990) says, "nobody can deny its power to actualize or to inhibit and to direct or to redirect a creative act" (p. 40). He goes on to suggest that as more research is performed, chance factors will emerge as far more influential than has ever been suspected.

Pasteur (cited in Simonton, 1988) is famous for this statement: "In fields of observation, chance favors only the prepared mind" (p. 396). In the sense that the prepared mind is one in which there is sufficient knowledge and intellect to understand the implications of a chance occurrence, and in which there burns an unresolved question (thus implying a nonequilibrium state), this statement by Pasteur accords well with the chaotic dynamic perspective.

Gruber's (Wallace & Gruber, 1989) acknowledgement of the role of chance in creativity follows along the same lines: "I agree that chance sometimes plays a prominent role--and that some role for chance may be in principle required in all creative accomplishment" (p. 10). He goes on: "The key point is that the evolution of human purpose transforms the operation of chance. Purposeful work that does not take cognizance of the chanciness of the world, including the inner world, will not lead to creative outcomes" (p. 11).

Simonton (1988) asserts that "the fundamental generating mechanism in creativity involves chance permutation" (p. 389) of mental elements (ideas, memories, emotional nuances, and the like), which are free to enter into various combinations. He proposes that mental elements have an intrinsic affinity for certain other elements, based upon past experience or learned conventions. For example, the concept of "school" calls up associations with such elements as books, teachers, cafeteria, algebra, boredom, and so on, forming stable configurations. Simonton further proposes that occasionally mental elements with no a priori affinity can, through chance permutations, form new configurations, "and large clusters of elements can form themselves spontaneously into highly ordered arrangements out of utter chaos" (p. 391).

Simonton (1988) predicts that a creative individual, whom he refers to as an "intuitive genius" (p. 400), can generate more chance permutations. His list of the characteristics displayed by such an individual mirrors those discussed earlier in the context of constraints which encourage movement away from equilibrium. For example, Simonton predicts that a creative individual has an ability to toy with elements and concepts and has a capacity for making remote associations between disparate ideas. He or she is independent, and is willing to take intellectual risks.

In Simonton's classification system, intuitive geniuses are distinguished from less creative individuals by having a richer reservoir of mental elements, thus increasing the number of possible permutations. They are distinguished from analytic geniuses by the number and flexibility of links between elements:

> On the one hand, the analytical genius has mental elements clustered into compact configurations arranged in a hierarchical order. The configurations are highly consolidated in that the elements within a configuration are linked by strong (cognitive or habitual)

> associations, and the elements within a configuration have minimal links with elements in other configurations. Configurations must be both "clear" (i.e., consist of strong associations among defining elements) and "distinct" (i.e., have minimal associations with elements outside the configuration) in order to form a hierarchical arrangement that might maximize the efficient distribution of knowledge.
>
> On the other hand, the intuitive genius, while having roughly the same quantity of mental elements, has a dramatically different way of retrieving information. Fewer connections are habitual or even properly symbolized, with a rich infusion of behaviorally active but infraconscious associations. Configurations are less clear and distinct, and thus knowledge is distributed in a more egalitarian fashion. Because mental elements are more richly interconnected, appreciably more ways exist of passing from one element to another. . . . This associative richness provides the mechanism for chance permutations. (Simonton, 1988, p. 402)

A simple extension of Simonton's formulation may serve to explain why creativity is more common in children than adults. Although children presumably have fewer mental elements than adults, their relative inexperience may manifest in less clear and distinct configurations, and more flexible connections. In other words, their sense of what is correct and incorrect is not as well developed, leaving them open to more chance permutations. As they mature and gain experience, they attain more stable configurations and routinized links with other configurations.

Martin Rosenman (1988) discusses the role of serendipity in scientific discovery. He describes a number of famous discoveries which were attributed to fortuitous circumstances and notes that "successful researchers watch closely and are willing to view the data from several different perspectives" (p. 136). He suggests that current funding procedures, requiring clearly defined research, leave little room for discovering anything truly new. He encourages scientists to attend to serendipity, for "by realizing that discovery involves a dynamic interplay between conventional scientific methods and chance in all of its forms, and by cultivating an aptitude for serendipity, scientists can greatly enhance their investigative powers" (p. 136).

David Feldman's (1991b) "Co-Incidence Theory" ascribes to chance a much wider sphere of influence. Here, rather than limiting the actions of chance to occasional fortuitous observations or configurations of mental elements, Feldman proposes that chance events can effect change in any and every factor that exerts influence on an individual. In his keynote address to the Ninth World Conference on Gifted and Talented Children, he said:

> The changes that are of interest to the Theory of Co-Incidence are not only those of the individual, but also changes in domains, bodies of knowledge, technology, fields, societies and cultures, and in particular the intercoordination among changes in all of these developmental phenomena. (Feldman, 1991b, n.p.)

In the same address, after discoursing at length about the various circumstances and events in Mozart's genetic endowment and the environmental context (including family, social, and historical contexts) which contributed to Mozart's musical genius, Feldman (1991b) says:

> When we witness a series of events, the magnitude, the majesty, the magnificence of which we associate with Mozart, they can only occur when the most delicate, precise, subtle, fortuitous and well formed process has been sustained over a sufficient period of time. To some extent the process cannot be influenced or controlled. To some extent it must depend on chance or unexpected events to provide critical catalysts and amplifiers along the way. (n.p.)

In essence, Feldman's Co-Incidence theory tries (using psychological terminology) to capture the dynamics of nonlinear dynamic systems subject to chaotic dynamics.

In the final analysis, and from the perspective afforded by chaotic dynamics, the role of chance in creativity both is and is not crucial. It is not crucial in the sense that the contribution of chance cannot take precedence over the role of the prepared mind. Both are necessary. A serendipitous observation or stray thought requires a mind moving in far-from-equilibrium states which can recognize the implications. A mind tied to equilibrium, and therefore not particularly sensitive, tends to let potentially transforming nuances slip by unnoticed.

Chance is crucial from the standpoint that it shapes the creative outcome. In a far-from-equilibrium state, a chance observation can give rise to fluctuations which then invade the system and cause it to self-organize. At a different moment in time, the chance that triggers self-organization may be slightly different (see Chapter II), and the specific form of the outcome would not be the same. Anyone who has had a computer hard disk malfunction and lost some or all of a piece of writing will understand. The rewrite is not the same as its lost predecessor, regardless of how faithfully the author tries to reconstruct the previous work. The second time around, conditions are inevitably different. The loss of the first piece may trigger an emotional state very different from that experienced during the first writing. Deadlines may be more pressing. One can be plagued by vague memories of phrases that seemed particularly graceful, and become frustrated that one cannot recall them exactly. On the positive side, one has already devised an overall structure, and can therefore proceed without making many of the mistakes which occurred during the first writing. A chance observation may occur during the second writing which triggers a new and more powerful perspective, leading to a much improved work and a feeling that perhaps losing the first was not so unfortunate.

Creativity is essentially unpredictable in a local and specific sense, and this is the contribution of chance. While theorists such as Howard Gruber insist that creativity is the result of purposeful work, thereby attempting to demystify creativity, even he would have to agree that even the creator cannot predict the exact shape of the final outcome.

Self Organization

The creative moment culminates when a system reorganizes or self-organizes from the far-from-equilibrium state to a new state or level of organization. Often in the literature on creativity this is referred to as the "Ah ha!" or the "Eureka" moment, and it is usually accompanied by a feeling of excitement, pleasure or perhaps euphoria.

In his characterization of the "flow" experience Csikszentmihalyi (1990b) describes what self-organization feels like. He speaks of a sensation of being in control, "or, more precisely, as lacking the sense of worry about losing control" (p. 59). Paradoxically:

> . . . it is not possible to experience a feeling of control unless one is willing to give up the safety of protective routines. Only when a doubtful outcome is at stake, and one is able to influence that outcome, can a person really know whether she is in control. (p. 61)

Csikszentmihalyi notes that, during flow, concentration is total, one's sense of time becomes distorted, and most specifically, there is a profound sense of enjoyment.

A good example is provided by Robert Grudin's (1990) description of a professor with abundant good ideas, but an inability to write about them. "When she sat down to express them, she immediately felt a variety of bad vibrations, including confusion, doubt, depression, distraction, and self-anger. In annoyance, she would postpone or avoid her work, acts rewarded inevitably by waves of guilt" (p. 78). Then, one summer, she attended a six-week seminar. Upon returning home she found her "voice."

The seminar experience had triggered a self-organization, and she started functioning on a new level. She attributes her new-found ability to express herself to several factors, all of which enabled her to diverge from her accustomed equilibrium. For example, her husband started helping with the children, thus allowing her more time, and relieving her of her feelings that everything depended upon her. Her time at the seminar "put her in a completely new role and context, thus establishing a matrix for her own renewal" (p. 79). During the seminar she was able to concentrate on a single subject and work uninterrupted. She found this brought her much pleasure. In addition, the seminar afforded intense peer encouragement, thus reducing the risks and increasing the benefits associated with creative endeavor. Finally, her husband bought her a word processor, thus allowing a greater degree of freedom while writing. Grudin (1990) notes that this professor came home from the seminar, "full of energy and resolve. . . . In a week she was writing, not out of guilt or obligation, but with a sense of exhilaration and self-expression. She has not stopped since" (p. 79).

This example serves to point out an interesting aspect of self-organization. Often, accounts of great creative discoveries speak of a momentary flash of insight, as though the process of creativity can take place in an instant. If the perspective afforded by nonlinear dynamics reflects reality, then in one sense this momentary event is the creative act. A system driven far-from-equilibrium by a variety of constraints is invaded by the fluctuations caused by some factor which becomes amplified by the nonlinear dynamics, and the whole system spontaneously and abruptly reorganizes to a new level of organization. This would seem to contradict theorists such as Gruber and Feldman who de-emphasize the importance of momentary insights, insisting instead that creativity is a sustained process, sometimes encompassing years.

However, nonlinear dynamics also can give rise to sustained processes. The new level at which a system arrives through self-organization may represent a new equilibrium, but it may not be stable. The research and writing of this dissertation provides a good example. The first burning question, engendered by reading Gleick's (1987) book Chaos, was whether the brain was a nonlinear dynamic system. The answer to that question immediately begat other questions, such as what such an insight might imply for the field of creativity research, and what the implications for education might be.

The list of questions and possible implications seems endless. In other words, if the constraints acting upon the system, such as the personality factors discussed above, are still pushing the system away from equilibrium, then one creative insight, or even a string of related insights, is unlikely to anchor the system to equilibrium. In addition, the newly discovered insights may themselves act as constraints favoring nonequilibrium.

The Two-Edged Sword

Before moving on to explore the implications that nonlinear dynamics have for educational practices, a warning is in order: chaotic dynamics is a two-edged sword. It seems plausible that creativity does arise from the workings of nonlinear dynamic processes. It might therefore seem reasonable to assume that if an individual is just driven away from his or her accustomed equilibrium, the result will be some creative insight. However, chaotic dynamics are fundamentally unpredictable. There are no guarantees that far-from-equilibrium experience will result in creative insights. There is only an increased possibility that the system may reorganize. Furthermore, there is no guarantee that the system will reorganize in a desirable direction. A creative idea may be the stuff which transforms a field; it may also be wrong, unimportant, or immoral. An individual driven from equilibrium may wax creative; he may also suffer a nervous breakdown, become ill, or retreat from reality.

Stepping aside from human creativity for a moment, an illustration of a nonlinear system in a far-from-equilibrium state should illustrate this point. This example is taken from the U.S. stock market. In October of 1987, the market had been consistently strong for the previous five years, causing the prices of many stocks to triple in value. This situation encouraged investors to "try their luck," and the stock exchange was kept busy with unusually high numbers of transactions. The volatility of the stock market is well known, demonstrating that the system is highly unstable and extremely sensitive to events. However, no one knew just how far from equilibrium the system had been pushed. No one saw the threshold to chaos approaching.

On October 14, two announcements hit the press. The Democrats announced new changes in the tax law that would lessen the attractiveness of corporate takeovers. At that time, such takeovers had been partially responsible for fueling the market. The second bit of news was that the most recent figures showed the international trade balance was sharply depressed. This information caused an upward pressure on already high interest rates in the United States.

As a result, James Baker met with the West Germans urging them to drop their interest rates, hoping that U.S. interests rates would drop as a result. Over the weekend of October 17-18, the domestic and international press reported that Baker and the West Germans had disagreed, and that interest rates would drop sharply in the United States in an effort to pressure the West Germans into dropping theirs. The reduction in the U.S. interest rate meant a loss for foreign investors, who immediately started selling off their U.S. investments.

By Monday morning, October 19, already aware that a crash was imminent, and in an effort to minimize the loss to their investors, large U.S. brokerage houses, such as Fidelity, implemented a massive sell-off. This pattern was then picked up by the large portfolio insurance accounts, foundering the market under the ensuing avalanche of sell-orders. In the course of a few hours, some of the historically most stable stocks, such as U.S. Steel, IBM, and Westinghouse, lost between 23 to 33 percent of their value. Less stable stocks lost more (Smith, Swartz, & Anders, 1987). Following the chaotic hours on Monday, and to some extent the days following, the market did self-organize at a new level. However, for many investors, "Black Monday" erased their life savings.

This example serves to illustrate that systems, and individuals, should not be pushed far-from-equilibrium heedlessly. While it is true that it is not possible to predict the behavior of a nonlinear system in terms of particular responses to particular variables, it is possible to make general predictions about probable responses. Intuitively, we know this to be true. If a hot-tempered individual is bombarded with experiences which ignite and feed his anger, one can be fairly sure that some sort of emotional eruption will occur. Keeping this warning in mind, the next chapter will discuss the educational implications of this nonlinear perspective.

CHAPTER V

IMPLICATIONS FOR EDUCATIONAL PHILOSOPHY AND STRATEGIES

Introduction

Nonlinear, nonequilibrium dynamics is fascinating, but the relevance to education may not be immediately apparent. What relevance it may possess hinges upon our understanding of the underlying purpose of education. Recent emphasis on programs stressing a "back to basics" approach and utilizing mastery learning techniques presupposes that the purpose of education is to help each student achieve a minimum level of competence in basic skills such as reading and mathematics. Presumably such universal competence would benefit society as a whole by ensuring that every adult possessed the skills needed to hold a job. Admittedly, an understanding of chaotic dynamics does not offer much toward achieving such a purpose.

However, if we are to meet and overcome the challenges facing our society and our planet, we will require individuals with more than basic competence. We will need individuals with great creative ability and tremendous flexibility;

individuals who are willing to step aside from conservative scenarios in order to find new routes to better solutions. If we are to survive, educational programs will need to do more than foster academic achievement; they will also need to nurture creativity.

Is creativity really as important as standard academic achievement? Roberta Milgram (1990) has conducted extensive research on cognitive processes over the years in order to answer this question. She tested adolescents for levels of types of giftedness, which she categorized as General Intelligence, Specific Intellectual Ability, General Creative Thinking and Specific Creative Talent. Eighteen years later, these adolescents having reached their mid-thirties, she found that there was a positive correlation between those who had achieved eminence as adults and those who previously tested high in either General or Specific Creativity. However, there was no correlation between adult achievement and high adolescent scores in General or Specific Intelligence. These results suggest that attempts to identify children who will become eminent adults should focus on creativity indexes rather than general intelligence or academic ability.

Further support for Milgram's (1990) idea that adult eminence results from creativity rather than just high intelligence is easily found. For example, Nouri Jaffar

(1984), speaking of genius as the highest level of manifest creativity, says that the contribution of a genius creates "progressive conditions of human advancement transcending generally accepted ideas by introducing new everlasting principles that defy old ideas and radically change man's views of the world and his place in it" (p. 46).

Examples from Western culture of individuals we revere as truly great adults are invariably those who were creative; those who were "ahead of their time," those who made great discoveries which revolutionized their field, those who brought a new perspective to their work. A list of such individuals is easy to compose: Leonardo Da Vinci, Albert Einstein, Madame Curie, Thomas Edison, Galileo, Martin Luther, Shakespeare, Keats, Beethoven, Virginia Wolf, Abraham Lincoln, Elizabeth Tudor, Winston Churchill, Picasso. Frequently the efforts of such individuals were not prized by their contemporaries: Edison's teachers told him he was too stupid to learn anything (Galbraith, 1984), Galileo was arrested for his "subversive" theories, Lincoln was shot, Luther was excommunicated, Beethoven was told by his music teacher that as a composer he was hopeless (Galbraith, 1984), Einstein was a poor student.

If, in order to meet the future's challenges, nurturing creativity becomes an educational priority, particularly for those students who are creatively gifted, then the perspective afforded by nonlinear dynamics may be helpful in providing a philosophical and strategic foundation for educational practices. Some implications for education, particularly those most closely tied to the foregoing discussion of creativity, will be suggested in this chapter. There will, however, be no attempt to discuss the full impact that a nonlinear systems perspective could have on education. The educational system is itself nonlinear, and is influenced by a host of dynamic nonlinear variables. As individuals concerned with various aspects of education encounter the principles of nonlinear dynamics they will find new insights and concomitant implications for their areas of major concern.

Nurturing Creativity: A Nonlinear Perspective

If, as was suggested in Chapter IV, chaotic dynamics underlies the phenomenon of human creativity, and if nurturing creativity is a legitimate and desirable educational goal, then the role of chaotic dynamics in the classroom must be addressed. What insights can chaotic dynamics offer? The first is that the probability of creative response is increased the further an individual (seen as a nonlinear dynamic system) moves from equilibrium. The second is that in a far-from-equilibrium state, individuals become exquisitely sensitive to changes in variables.

Promoting Far-From-Equilibrium Experience

Driving an individual far from equilibrium is not difficult, but carries the risk of disaster. As Maslow (1968) demonstrated, unless basic needs, such as the need for safety, are met, an individual is unlikely to achieve the self-actualizing level of development, the level that Maslow associates with creativity. When a perceived risk seems unacceptable, or when one's emotional or physical safety are threatened, one is likely to respond to disequilibrium constraints by forcefully attempting to return to equilibrium. For example, consider a mother who is wholly occupied with some creative endeavor, who has assigned it top priority. Suddenly, her child is seriously injured in an accident. Priorities change rapidly. No longer is she focused on exploring new perspectives and breaking through conceptual barriers; now her whole desire is to return the child and the family to a near semblance of normality. Only after life has once again assumed its accustomed pace and flavor can she again allow the drift away from equilibrium.

This example does not rule out the possibility that some individuals respond to threatening circumstances with remarkable creativity. Perhaps they are driven by the realization that the risks of not producing a creative solution outweigh the risks inherent in the situation. For example, the currently popular television series McGuyver illustrates on a weekly basis the ability of an intelligent individual to consistently avoid life-threatening situations through inventive chemistry and engineering.

In an educational setting, it is more appropriate to allow students to move away from equilibrium rather than driving them from it. How is this accomplished? One way is by reducing or eliminating barriers that discourage disequilibrium states. Another is by exposing students to new situations and perspectives. Interestingly, though perhaps not surprisingly, there are many strategies already employed in the education of gifted and talented students which are founded upon these principles and which would benefit all children (for example, see Clark, 1988).

Reducing Equilibrium Constraints

Risk and the consequences of failure are major factors that discourage departure from equilibrium. According to Rubenson's (1990) psychoeconomic theory, a risk will be entertained only when the perceived benefit of taking the risk is greater than the possible consequences of failure. Risk in an educational setting is represented by the possibility of receiving bad grades, and by eliciting ridicule from teachers and peers. For example, consider a first grade art lesson in which the students are to paint flowers. The teacher shows the class a painting that he did of some daisies, and shows the students how to reproduce his creation. One student becomes fascinated at the way the watercolor is soaked up by the paper, and instead of a neat rendition of daisies, creates a garden full of "flowers" vaguely suggestive Monet's "Water Lilies." The teacher has several choices. He can show the class the flower garden and comment on the student's creative vision. He can quietly applaud the student's efforts. He can tell the student that the assignment is to draw daisies, and that she should try again. He can hold up the student's painting as a negative example, thus calling on other students to add their censure to his own. He can turn the exercise into an art contest, judging the merit of each student's effort. In other words, the level of risk that the student experiences is determined by the classroom climate the teacher creates. A student whose unconventional efforts are applauded is more likely to experiment the next time; the one whose efforts are ridiculed is less likely to diverge from convention.

Currently, many of the educational strategies such as Mastery Learning and DISTAR (Becker, 1986) introduce new concepts and skills in tiny increments in order to minimize the possibility that a student may fail to achieve mastery. Failure is viewed as demoralizing and a threat to self-esteem, and is to be avoided at all costs. Success is required at each level before a student can advance to the next level. Gardner (1989) observed the same process in Chinese arts education:

> All teachable performances are broken down into the smallest possible units, for presentation and mastery one step at a time. So far as I could tell, there is little effort to provide a rationale to the students: this is just the way things are done. And, again consistent with an empiricist (as opposed to a rationalist) view, there is little interest in cognition, ideas, abstract thinking: instead, what is at issue is the correct observable form of performance. . . . A school lesson is not considered successful unless all students achieve a perfect performance. (p. 277)

While such methods may ensure success in mastering skills, the focus on success acts as an equilibrium constraint. As Gardner (1989) also notes: "Of course, so long as success is required, genuine experimentation cannot occur" (p. 237). What is not recognized in such educational philosophies is that the onus attached to failure is generated by the classroom and social environment. If success is de-emphasized while experimentation is valued and rewarded, if failures are treated as opportunities for further learning, children will be more likely to stretch themselves beyond the conventional. Even in China, a culture with a centuries-old tradition of strict adherence to convention, Gardner observed children demonstrating creative behavior when equilibrium constraints were relaxed. He tells, for example, of a young music teacher who discarded the standard curriculum and encouraged his young students to compose their own music:

> He tells me that many of his fellow teachers cannot abide the loud play and chaos that accompany such exercises, but he feels that such "letting go" is an essential part of the musical creativity he is trying to foster. Unless students imbibe atmosphere in which they feel they can explore, try things out, and even fail, they will be too conservative. The rest of China needs to hear this message from one twenty-seven-year-old music teacher! (Gardner, 1989, p. 234)

A similar message is communicated by Amabile (1989, 1990) when she speaks of the negative effect that outside evaluation has on creative production. Children are particularly sensitive to the opinions of others, and frequently accept those of an adult as "fact." Rather than following their own vision, they may try to please the judge, whose own expectations may be at odds with the student's. In reviewing the literature on play and its relation to creativity, Meador (1992) attests to the importance of allowing young children to develop their creative capability through free play opportunities. Significantly, the author defines free play as a time in which children are in a risk-free environment and fear no evaluation or failure.

In a similar vein, rewards offered for creative endeavor can act as equilibrium constraints (see Chapter IV).

Presumably this results because the desire to earn the reward entails the need to satisfy the expectations of the one offering the reward, again interfering with the individual's free creative exploration.

Another way to reduce equilibrium constraints is to foster a classroom environment in which students are respected and appreciated for their own peculiar abilities and intensities. Piechowski and Colangelo (1984) have demonstrated that gifted students are frequently those who have an array of "overexcitabilities" (see Chapter IV). In particular, the imaginational, emotional, sensual, and to some extent the intellectual overexcitabilities encourage such students to stray from equilibrium, increasing the likelihood that they will be creative. These same traits are also frequently experienced by classroom teachers as annoying or threatening, and the students are made to understand that they are not normal. Rather than trying to control or tone down the intensity of these students, their energy should be understood, supported, and perhaps channeled into productive, creative outlets.

Encouraging Disequilibrium

For the purpose of this discussion, disequilibrium represents any state in which a student must stretch beyond current skills or knowledge. The further a student stretches, the further from equilibrium she moves. As discussed above, much currently popular curriculum progresses by means of very small steps which barely require a student to stretch. In order to nurture creativity, greater challenges to understanding must be allowed and encouraged. However, according to Piaget's principle of moderate novelty (see Ginsburg & Opper, 1988), material presented which is too novel, which has no point of reference to which a student can attach meaning, represents frustration rather than challenge. In terms of disequilibrium dynamics, a challenge that is too far beyond a student is threatening, and will likely encourage a rejection of the challenge and return to equilibrium conditions.

Csikszentmihalyi (1990b) addresses the same principle in his discussion of flow. As mentioned in Chapter IV, flow is a state experienced when the level of challenge to one's skills or knowledge is sufficient to abolish boredom, while remaining within the realm of capability. Intrinsic to Csikszentmihalyi's notion of challenge is the concept of interest. An activity in which a student has little interest is unlikely to be perceived as providing a worthwhile challenge. And an activity that is not challenging quickly becomes boring, and hence unenjoyable. In contrast, a passionate interest is likely to offer challenges which the student is only too willing to pursue. The activity then becomes autotelic: its pursuit is its own reward.

The role of the educator then is to encourage such challenges by attending to and supporting the interests of students, perhaps using such interests as a vehicle for mastering skills. Cohen (in press-b) illustrates this principle using the example of a young girl who is crazy about horses. Her interest in horses can be supported by encouraging her to read all about horses, thus bolstering her reading skills. Research skills could be introduced and practiced by challenging her to investigate some aspect of equine lore that she finds particularly fascinating or is completely outside her area of knowledge. She could research, for example, selective breeding and its effect on the modern thoroughbred. Perhaps in the course of her research, she discovers she wants to take photographs of racehorses to illustrate her discoveries. She will thus need to learn how to use a camera, and how to compose good pictures. This could lead to new area of interest and challenge. Gruber (1988) refers to this burgeoning array of interrelated interests as a network of enterprises, and sees it as the hallmark of creative individuals. Finally, as she reports her findings to the class, she is practicing speaking skills. An added benefit of such presentations is that they can serve to spark the interest of other class members, who may then accept similar challenges to pursue their passionate interests.

Change of Perspective

A change of perspective from which something is viewed necessarily entails a new understanding of the thing or phenomena under study. That is why orthopedic surgeons insist that X-rays photographs be obtained from several different angles when a bone break is suspected. If the bone is broken, and the two ends have overridden each other such that one slides behind the other, from one angle the bone will appear perfectly straight and whole. A view taken from a somewhat different angle will reveal a complete break and the overriding dislocation. If one doctor saw only the first film, and another doctor saw only the second, they would disagree violently about the treatment the patient required. If, on the other hand, the information revealed by each film is integrated, then the doctors know that the bone is broken, and exactly how it is displaced.

When the concept of perspective is applied to ideas rather than concrete items such as bones, a change in perspective has the potential to make the perceiver reassess previous knowledge in light of the new perspective. Such a process necessarily entails some degree of disequilibrium, and therefore carries the potential to foster creative insights. Frequently, a newly encountered perspective which radically departs from one's accustomed point of view can seem to be nonsense. It is in trying to make sense out of nonsense that our conceptual boundaries are approached and sometimes breached. As Gary Zukav (1979) says:

> The importance of nonsense hardly can be overstated. The more clearly we experience something as "nonsense," the more clearly we are experiencing the boundaries of our own self-imposed cognitive structures. "Nonsense" is that which does not fit into the prearranged patterns which we have superimposed on reality. . . . Nonsense is nonsense only when we have not yet found that point of view from which it makes sense. . . . Those scientists who establish the established lines of thought, however, are those who do not fear to venture boldly into nonsense, into that which any fool could have told them is clearly not so. This is the mark of the creative mind; in fact, this is the creative process. It is characterized by a steadfast confidence that there exists a point of view from which the "nonsense" is not nonsense at all--in fact, from which it is obvious. (p. 117)

A natural way to encourage students to view concepts or phenomena from different perspectives is to employ an interdisciplinary approach. Similar to the doctors viewing the broken bone from different angles, approaching any subject from different angles allows for a blending of information. This dissertation provides such an example by attempting to suggest a new understanding of human creativity through the integration of the perspectives of several disciplines.

A wonderful example of how curriculum can be structured to include an interdisciplinary focus is provided by the medical school at Maastricht University in the Netherlands.

Standard medical curriculum requires that students study each organ system in isolation, focusing on physiology and pathology. In contrast, at Maastricht, interdisciplinary problems are posed, and students learn as a result of trying to find the answer to those problems. For example, students might be asked to thoroughly investigate how blood circulates throughout the body. They must understand and relate all the factors which influence this process. Small groups of students, in concert with a faculty advisor (who plays a somewhat Socratic role), investigate each problem for six weeks. All of their energy is devoted to this one question. A full answer will plunge them into such subjects as blood composition, physiology of arteries and veins, the mechanics of the heart along with its local innervation and the control from the brain, the effect of substances such as hormones and coagulants, and the effects of conditions such as cold, heat, exertion, fear, and disease. The list goes on, and is potentially endless.[1]

In such a system, the myriad perspectives that a student encounters while questing for the answer to such problems serve as constraints that tend towards disequilibrium. In order to arrive at a new level of equilibrium, the

[1]This insight was presented privately by Professor Wijnen of Maastricht University to participants of the Ninth World Conference on Gifted and Talented Children, July 31, 1991.

students must construct their own understanding, their own integration of encountered knowledge with that which they already possess.

Similar integrations are possible whenever a subject is studied within its total context. Take, for example, Hawthorn's (1970) book, The Scarlet Letter. Generally, this book is presented to students isolated of all but the most rudimentary context. The experience of reading this book becomes far richer when the historical context, both of the time the story was set and Hawthorn's era, the nineteenth century, is explored. Further areas for exploration might include the status of literary forms at the time Hawthorn wrote, as well as his personal history. What motivated him to write this story? Did he write any others with similar themes, similar characters, similar symbolism? The symbolism used throughout the book also has a cultural history which might enrich understanding. More importantly, what does this book says to each individual reader? Is there any interface between the experience of the author or the characters and the reader? And how will the reading of this book shape the reader's understanding of other books and experiences?

Shore, Cornell, Robinson, and Ward (1991) looked at recommended practices for educating gifted and talented students. They note that although many authors call for a multidisciplinary approach, little direct research has been done to support this recommendation. However, they also note:

> At the frontiers of knowledge pursued by advanced scholars, the need for a multidisciplinary approach may be obvious, in order to make sense out of unfamiliar events. The young learner may be in a comparable situation, but this has not been studied directly. The widespread interest in "whole language" curriculum reflects this different view; one can at least begin to exercise the processes underlying high-level creative endeavors from a basis of little specific knowledge. Both can then grow. (Shore et al., 1991, p. 89)

Another educational model which encourages new perspectives and far-from-equilibrium experience is Barbara Clark's (1988) integrated learning approach. Rather than relying primarily on interdisciplinarity to provide breadth or change of perspective, this model strives to help students use and integrate the four aspects of mental function: thinking, sensing, feeling, and intuition. By accessing, acknowledging and interweaving the insights afforded by these different mental faculties, students attain a richer understanding of subjects. Additionally, this model's acceptance of intuition as a legitimate source for posing and answering questions allows students to diverge from equilibrium, thus encouraging creative responses.

A more radical exercise in changing perspective, one guaranteed to promote disequilibrium, is embodied in the struggle with paradox. For example, paradoxical puzzles called "koans" are used by Zen Buddhists to promote new perspective and understanding (see Zukav, p. 205). A famous koan is, "What is the sound of one hand clapping?" There are no single correct answers to a koan; rather, each student must find within herself a new mental structure which makes sense out of the paradox.

Jaffar (1984), in his study of scientific geniuses, assigns paradox a central role in creative development. He says: "Paradoxes play a significant role in the development of science. It is well-known that paradoxes, which were not settled within the framework of classical physics, resulted in the elaboration of the theory of relativity" (p. 59). He goes on to say:

> Extraordinary ideas undermine accepted notions, questions are treated from unexpected angles, unconventional views are taken of conventional things, problems find extraordinary solutions. . . . In short, it is worthwhile to take a look at a phenomenon of the external world from an unusual angle and try to see it in a new way, and not through the prism of conventional ideas. (Jaffar, 1984, p. 59)

His advice is reminiscent of a favorite saying of Sherlock Holmes, "How often have I said to you that when you have eliminated the impossible, whatever remains, however improbable, must be the truth?" (Doyle, 1981, p. 163).

While Western schools may not be structured to utilize koans for individual growth, a similar effect can be gained by discussion of controversial subjects. Controversy exists in a situation because there are at least two defensible sides to an issue. A currently volatile example is provided by the abortion issue. An individual who staunchly sees only one side of such an issue is anchored to equilibrium, and in extreme cases refuses even to hear, much less acknowledge, the arguments tendered by individuals on the other side. However, if an issue is truly controversial, if there are strong points to be made on both sides, then as understanding dawns concerning the legitimate points of the opposing point of view, the individual moves away from equilibrium, and perhaps towards a new perspective on the problem.

There are other educational practices currently advocated for gifted and talented children which also encourage exploration beyond equilibrium. For example, posing open-ended questions encourages students to stretch beyond their usual measure. Open ended projects, particularly those with real-life applicability, and which are founded in a student's own interests also encourage such exploration (for an example, see Renzulli & Reis, 1986). Divergent thinking exercises such as those suggested in the Creative Problem Solving program (Isaksen & Treffinger, 1985) are admirably suited to breaking conceptual boundaries. Teaching students about fractals and nonlinear dynamics could provide another means of encouraging boundary breaking.

The concept of fractal objects existing between dimensions, (as described in Chapter II) is unconventional, and thus invites students to move away from equilibrium. A study of the Mandelbrot set, with its infinite possibility for regression without loss of complexity, can introduce students to the importance of relative scope and scale. They may discover that objects or concepts that appear at one level to be chaotic, at another scale reveal patterns. Finding patterns that are not obvious on the surface requires students to reach within themselves to find a connection between their conceptions about pattern and the object or concept they have encountered. Such a discovery might encourage students to observe more closely and think about their observations, rather than accepting everything at face value. In short, any practice which encourages students to think beyond the conventional has the potential to nurture their creative abilities by acclimating them to a state of disequilibrium.

Far-From-Equilibrium Sensitivity

To suggest that students should be driven indiscriminately away from equilibrium in an effort to provoke creative responses would be irresponsible. As mentioned in Chapter IV, chaotic dynamics may lead to a reorganization, but cannot guarantee the direction of that reorganization, or the desirability of the eventual state. Nonetheless, nonequilibrium occurs naturally, sometimes as the result of the "slings and arrows of outrageous fortune," and sometimes in response to new stimuli or new challenges.

Teachers need to understand that in a far-from-equilibrium state individuals can display exquisite sensitivity, not only to "initial conditions," such as experiences at home, but also to the smallest incident or utterance. On the one hand, such sensitivity imparts potentially incalculable importance to every word, gesture, or event in the classroom. A casual pat on the back or a smile can provide encouragement far beyond what the teacher imagines. A humorous comment meant to cheer can be interpreted by a student as unimaginably degrading. On the other hand, the most carefully planned and executed lesson, one designed to spark interest and challenge perceptions, may have no effect at all. The far-from-equilibrium student may be wholly involved in the implications of last night's tiff with his girl friend and not even hear the teacher. Prediction is impossible, and therefore teachers need to approach their task with a certain amount of humility.

The perspective afforded by nonequilibrium dynamics suggest that children are more easily diverted from equilibrium than are most adults. Having a smaller fund of experience on which to draw, children often do not possess automatic responses to particular situations. Similarly, when encountering new information or circumstances, they may not have had comparable experiences which could help inform their response. They are therefore more easily swayed by the opinions of influential adults. Simply put, children are impressionable, and a teacher needs to aware of the potential impact that his point of view may have on his students.

The problem is that one is never very sure what factors become influential. For example, consider the aforementioned debate on abortion. Oversimplifying a bit, there are four viewpoints on this issue: those who believe women should have the power to make decisions about their own bodies; those who believe that abortion is wrong and should be banned; those who are profoundly uninterested in the question; and those who, for a variety of reasons, are undecided. The individuals in the first three groups have all found their own equilibrium with respect to this question, and consequently something momentous would have to happen to make them change their stance. For the fourth group, however, equilibrium has not been achieved. To varying degrees, the individuals in this group are influenced by events and arguments, and it is to these individuals that all of the rhetoric and posturing is addressed. What cannot be ascertained a priori is the effect that particular strategies will have on particular individuals. Showing a dead fetus in a bottle to one individual may swing her opinion violently towards the anti-abortion pole. To another, such a display could have the opposite effect. A third individual may have no reaction. The difference in response arises from factors outside the control of those who wish to be persuasive. Differences in personal and family history, socio-economic class, personality factors, religion, mood, age, gender all contribute to the reaction that such a display might evoke.

Teachers face the same kind of problem. They cannot know in advance the reaction that every student will have to an educational intervention. Recent literature on the role of prior knowledge in determining how individuals construct meaning has underlined this difficulty (see, for example, Leinhardt, 1992; Pazzani, 1991; Riley & Shapiro, 1990). Leinhardt notes: "Knowledge is a complex network of ideas, facts, principles, actions, and scenes; therefore, prior knowledge is more than a building-block of information. It can facilitate, inhibit, or transform a common learning task" (1992, p. 22). Unfortunately, the difficulty of determining the effect of an intervention is not limited to prior knowledge of the subject area in question. As suggested in the preceding paragraph, a whole host of factors beyond the control of educators come into play. One can strive to make explicit a student's prior knowledge of, for example, William Blake's poetry, in an effort to mitigate the effects of misconceptions and to build on existing foundations. However, in a class full of students, a teacher may have a child that is chronically malnourished, one who recently witnessed a virulent argument between his parents, another who fell in love yesterday, and perhaps a few who have been living on the streets. Their reactions to Blake's poem The Clod and the Pebble will probably vary considerably.

> 'Love seeketh not Itself to please,
> Nor for itself hath any care,
> But for another gives its ease,
> And builds a Heaven in Hell's despair.'
>
> So sung a little Clod of Clay
> Trodden with the cattle's feet,
> But a Pebble of the brook
> Warbled out these metres meet:
>
> 'Love seeketh only Self to please,
> To bind another to Its delight,
> Joys in another's loss of ease,
> And builds a Hell in Heaven's despite.'
> (Blake, cited in Frye, 1953, p. 37)

Each of these students can be considered to be far-from-equilibrium, certainly with respect to their living experience and possibly with respect to the new poem. Their experience with the poem can range from profound disinterest to finding the poem a source of enlightenment. Its impact depends with near infinite sensitivity on a undefinable host of factors. No one can predetermine which phrase or image might resonate with an individual's particular state of being and elicit a unique, creative response.

Rosenblatt (1983) advocates an approach to literature which centers on student response rather than focusing on such devices as structure, characterization, setting and theme. In essence, this approach utilizes students' non-equilibrium responses to nurture independent thought and creativity. Literary skills and terminology are then taught as adjuncts to the literature experience, rather than as ends in themselves. Robert Probst (1988) portrays the teacher's role in such an approach as necessarily as responsive to the nuances alive in the classroom as the students are sensitive to the literature:

> They need to be open to the possibilities that arise in the thirty different responses--and thus the thirty different poems--that they have before them. . . . They must remain open to the possibility that something unexpected will arise in the talk and be prepared to capitalize on it. That uncertainty may be nerve-wracking, but it has its rewards. It keeps the class alive, allowing a vital exchange of ideas rather than the working out of a script. Both students and teachers need to develop a tolerance for ambiguity in such a classroom. There may rarely be a satisfying consensus at the close of the lesson. Individuals are responsible for their own conclusions and summations. (p. 38)

Feldman (1991b), in his address to the Ninth World Conference on Gifted and Talented Children, suggested another role for the teacher of creative individuals: that of managing co-incidence. While acknowledging that one cannot possibly control all factors which influence the development of a genius such as Mozart, Feldman (1991b) suggested that an astute mentor can "harness" co-incidence by "taking advantage of opportunities, responding to possibilities, controlling the course of events to the degree possible and coordinating and directing the process patiently and wisely. It also means knowing when to let go" (n.p.).

Philosophical Implications

Gleick (1987) describes the evolution of a snowflake as a nonequilibrium process, and his description resonates with our understanding of how children develop:

> As a growing snowflake falls to earth, typically floating in the wind for an hour or more, the choices made by the branching tips at any instant depend sensitively on such things as the temperature, the humidity, and the presence of impurities in the atmosphere. . . . The nature of turbulent air is such that any pair of snowflakes will experience very different paths. The final flake records the history of all the changing weather conditions it has experienced, and the combinations may as well be infinite. (p. 311)

In a similar fashion, a child at any given moment is the result of the combined influences of every experience coupled with his own genetic endowment. Two children may sit in the same classroom day after day, receiving the same instruction, and yet, because of their diverse histories, they may receive that information differently.

What nonlinear dynamics really suggests for educators is that teaching is more an art than a science. Science, at least viewed from the conventional positivist, empirical viewpoint, deals with phenomena which can be predicted, and which yield reproducible results when subjected to the same conditions. However, with nonlinear systems, particularly those in a nonequilibrium state, it is not possible to exactly reproduce all the conditions of an experiment, and even the most minute difference in conditions can radically change the outcome (see Chapter II). Exact prediction is therefore not possible. This principle is either intuitively or overtly understood by those who currently encourage or indulge in the various forms of qualitative research (see Borland, 1990). For this new breed of researcher, context is crucial, and findings cannot with impunity be generalized to other populations and conditions.

For the teacher, this means that there is no "surefire" recipe for successful teaching. There is no guaranteed, never-fail strategy for classroom management, no one perfect algorithm for teaching every student a concept such as fractions, or a skill, such as handwriting. An effective teacher knows that she needs a variety of strategies for teaching any subject or skill and must be ready to create a new strategy for the student who still fails after the teacher's repertoire has been exhausted. The teacher's intuitive ability to choose effective strategies, and to modify them as necessary in the face of a particular situation or an individual's needs, is an exercise in artistry. It is art that may be informed by scientific research, but it is art nonetheless.

Teachers also need to understand that they too are nonlinear dynamic systems. An unusually challenging student, situation, or curriculum, may push the teacher away from equilibrium, precipitating some response. One speculates that inspired teachers can be differentiated from the uninspired by their response to such nonequilibrium states. The nonlinear dynamic perspective suggests that good teachers respond by creating new strategies for coping with students, or by developing a new perspective which can accommodate the situation. These are the teachers who invariably claim that they continually learn and grow as a result of their interactions with pupils. In contrast, those who are "burned out" or who are threatened by challenging students will most likely respond by consciously forcing a return to equilibrium, usually by insisting that students conform to "normal" or rigidly defined expectations.

The beginning of this chapter suggested that the purpose of education should be to maximize the potential of each individual. The perspective afforded by nonlinear dynamics suggests that in order to do this we need to develop individual-centered schools, perhaps modeled after those being pioneered by Howard Gardner (1989). Gardner notes that currently influential critics of the American educational system are calling for uniform education: "Uniform education mandates the same curricula for all children, taught in the same way, and with the same tests administered regularly to all children" (1989, pp. 293-294). Unfortunately, as William Blake so aptly put it in his poem The Marriage of Heaven and Hell, "One Law for the Lion and Ox is Oppression" (cited in Frye, 1953, p. 134). Gardner (1989) would agree with Blake, and maintains that "not all individuals have the same mental abilities and profiles, any more than they are identical in appearance or in personality" (p. 294). He then goes on to say:

> Since there is much more to learn than there is time for learning, it is essential to make choices of what to learn and how to learn it. An individual-centered school takes these differences seriously and offers curricula, assessment procedures, and educational options responsive to each of the students in its charge. (Gardner, 1989, p. 294)

The Need for Balance in the Curriculum

Even chocolate loses its savor when eaten in excess. Indeed, anything indulged in excessively can be unhealthy, including nonequilibrium states. The purpose of this dissertation is not therefore to suggest that students should always function in a far-from-equilibrium state. On the contrary, if Pasteur was correct in saying that "chance favors the prepared mind," then attention must also be paid to equipping the minds of students so that they can become the kinds of creative, productive adults we so desperately need. The suggestion here is that an individual's mind is prepared not only by cramming it with knowledge and training it to perform skillfully, but also by exercising its abilities to conjure up creative ideas from the stuff encountered in the chaotic, far-from-equilibrium state. Skills, knowledge, and the willingness to playfully manipulate knowledge in light of experience, are all necessary for creativity to manifest. Without some degree of knowledge and skills, there is little material with which to weave a novel idea. Without playfulness and the ability to tolerate ambiguity, all the knowledge and skill in the world will not propel the individual beyond his conceptual barriers.

In his comparative study of Chinese and American arts education, Howard Gardner (1989) has been struck by this need for balance:

> As I consider the Chinese and the American educational scenes over the past few decades, I feel that each has proceeded too far in one direction, without paying sufficient attention to the alternative route. In the America of the 1960s and early 1970s, there was such antipathy toward tradition and fear of rigidity that a "progressive" or "creativity" stance prevailed uncritically in many quarters; . . . in the absence of requisite knowledge and skill, disorganization, ineptitude,

> and even chaos followed. . . . Conversely in China, there has been such a fear of rebellion, or of the perils of openness, that the educational system has bet almost completely on traditional forms and approaches. This option yields lovely performances on the part of young children but, in the absence of competing messages at home or in the streets, one ends up with an unimaginative adult population and a stagnant society. (p. 297)

Balance can be achieved. Strategies which combine skill and knowledge acquisition with creative thinking already are advocated by many who are conducting research in talented and gifted education (see for example, Amabile, 1989; Clark, 1988; Cohen, in press-b; Meador, 1992; Renzulli & Reis, 1986; Shore et al., 1991). However, isolated strategies are not enough. Current emphasis in educational practice is clearly weighted towards skill and knowledge attainment. Methods used such as DISTAR and Concept Attainment (see Becker, 1986) advocate the presentation of logical, linear-sequential exercises designed to allow the student to progress by steadily building on previous knowledge and skill. Movement away from equilibrium is discouraged. Such strategies are founded upon a linear, computer-like conception of brain function. This deep seated, often unconsciously held metaphor represents an obstruction to achieving the much-needed balance. The nature, extent and influence of this barrier will be addressed in the next section.

The Influence of Brain Metaphors on Education

One reason humans create metaphors is to attempt to explain and understand phenomena that are beyond rational understanding. Unfortunately, the attributes of a metaphor and its object can become confused, and the unwary can assume mistakenly that some or all features of one are shared by the other. For example, one currently common metaphor is that the brain is a computer. Superficially this may be true. Both brains and computers receive information, process it, and produce some form of output. However, as discussed in Chapter III, the brain is a highly nonlinear system, and its functioning can no longer adequately be described as a computer-like linear-sequential process.

Nevertheless, this metaphor persists, and much educational strategy is based upon this view. A quick survey of some of the metaphors which have informed Western education since the Renaissance will provide a foundation for the argument that sooner or later, educational theory will need to change in order to reflect the newly emerging understanding of the behavior of complex nonlinear systems.

The first example is drawn from the English Renaissance, a time when, despite the restructuring of the church, basic understandings about man and nature were still much under the influence of medieval theology. Since the time of

Augustine (and reinforced by the arguments of Aquinas), Christian theologians and clergy had emphasized that the human mind belonged to God, but the body belonged wholly to Mammon. One needed to guard against contaminating the mind with bodily desires, needs, and lusts. This duality continues to influence thought today, as evidence by those who insist that mind and brain are not synonymous.

An examination of Spencer's (1978) The Faerie Queene (Book II, Canto IX, 50-58) illustrates sixteenth-century understanding about mental functioning. The poet utilizes allegorical figures to characterize three separate brain functions. He describes the mind as a tower, the workmanship of which excels that of all other worldly works, and which is most like God's own heavenly tower. This tower is inhabited by three sages. The first is Imagination, who resides in the forepart of the tower. Imagination is characterized as a melancholy young man who is never idle and is endowed with sharp foresight. His room buzzes with flies that represent "idle thoughts and fantasies, devices, dreams, opinions unsound, shewes, visions, sooth-sayes, and prophesies" (stanza 51). The second room is inhabited by Judgment, a man of "ripe and perfect age" (stanza 54), who spends his time meditating upon the wisdom of ancient sages, and upon philosophy and science. In the third room, the "hindmost" of the three, lives Memory, an "old old man, halfe blind, Yet lively vigour rested in his mind" (stanza 55). He records events as they occur so that the memory of these can not perish. He is surrounded by scrolls and books, some of which are "worme-eaten, and full of canker holes" (stanza 57).

This description of the human mind, couched though it is in allegorical images, reveals not only how people in the sixteenth century understood mental function, but also which of the three aspects was most valued. Imagination, although needed for its foresight, can also lead one astray through idle fantasies. Characterized as a young man, Imagination thereby partakes of the instability and intemperance associated with youth's inexperience. Imagination is clearly the least valued of the three faculties, and must be rigorously restrained by the mind's more rational faculties. In contrast, the characterization of Judgment is entirely laudatory, and it is highly significant that Judgment is envisioned as relying on the wisdom of the ancients. Memory, though afflicted with the infirmities of age, is valued for its record keeping activities. Without Memory, Judgment would have little material from which to glean wisdom.

The relationship between this view of the human mind and educational practice in the sixteenth and seventeenth centuries is easily demonstrated. First, imagination and creativity was neither valued nor encouraged. Even in the arts, the ideal was to perfect already existing forms rather than to invent new expressions. For example, Shakespeare's plays were all rewrites of old plays, and/or dramatizations of well-known historical events. Formal schooling (for those who could afford it) consisted of studying and memorizing the texts of the ancient Greek sages, such as Aristotle, Plato, Hippocrates, and so on. Modern innovations were not viewed as acceptable curricular content, nor was questioning of the accepted knowledge and paradigms encouraged. Speaking, as we can believe, from first-hand knowledge, Francis Bacon (1939) tells us, in his Novum Organum, originally published in 1620:

> In the customs and institutions of schools, academies, colleges, and similar bodies destined for the abode of learned men and the cultivation of learning, everything is found adverse to the progress of science. For the lectures and exercises there are so ordered, that to think or speculate on anything out of the common way can hardly occur to any man. And if one or two have the boldness to use any liberty of judgment, they must undertake the task all by themselves; they can have no advantage from the company of others. And if they can endure this also, they will find their industry and largeness of mind no slight hindrance to their fortune. For the studies of men in these places are confined and as it were imprisoned in the writings of certain authors, from whom if any man dissent he is straightway arraigned as a turbulent person and an innovator. (p. 64)

The emphasis on the importance of a "classical" education persisted well into the twentieth century, and in some ways still persists. This was demonstrated a few years ago by the popularity of the book entitled Cultural Literacy by

E. D. Hirsch (1987) which included an exhausting listed of facts that every "educated" person should know.

The Mechanistic View of Brain and Mind

Before the turn of the century, when the industrial revolution was well underway and machines had become an important part of everyone's life, Santiago Ramón y Cajal put forth the suggestion that the brain was made up of innumerable separate parts which he called neurons. These neurons communicated with other neurons through "synapses," a term coined by C. S. Sherrington in his book, The Integrative Action of the Nervous System, published in 1906 (see Churchland, 1986, p. 29).

These discoveries, along with those arising from lesion studies that demonstrated that different areas of the brain seemed to be responsible for discrete functions, such as speech, memory, or emotion, led to a new, yet soon widely held metaphor for the human brain. Borrowing directly from the predominant technology of the time, those interested in the brain began viewing it as a biological machine. Although Descartes, known for his fascination for clockworks and fountains, described the brain in machine terms back in the seventeenth century, the metaphor did not immediately catch on. An understanding of machinery was not widespread until the industrial revolution. The metaphor comparing the brain to a machine became accepted as those outside the field of neuroscience grasped the similarities.

This new understanding translated quickly into the educational reform movements of the day. If people were controlled and motivated by the biological machines in their heads, then the most logical route for educating them would be a factory model. The Lancastrian model for educating the masses of urban children was the most extreme example of this thinking (Tyack, 1974). Schooling under this model consisted of rote memorization of facts: arithmetic facts, geography facts, historical facts, spelling facts. For those not destined for higher education, the purpose of schooling was not to encourage students to sharpen their judgment by meditating on the wisdom of the ancients, but rather to cultivate the behaviors and skills necessary to take their place in the new industrial work force (Nasaw, 1979).

The Influence of Computers on Our Conception of Mind/Brain

The later half of this century has seen another shift in our conception of how the human brain works. This change has evolved not so much as a result of new advances in neuroscience as from the development of computers. These machines, able to "out think" (at least in serial computation) human beings to the same degree that a steam engine could out-work the folk hero John Henry, have had a profound effect on the way we think about intelligence and thinking. Rather than modelling computers after neural circuitry (which we still know relatively little about), brain researchers began using the computer as a metaphor to illuminate brain function. As mentioned in Chapter II, brains were conceived of as having some central executive function able to synthesize input and direct output, and this conception has supported the idea of a mind/brain split.

The result of such thinking has been a belief that humans process information in the same hierarchical, serial manner that computers employ. This conception has led to educational strategies emphasizing the modifying of input so as to achieve desired output. Practically speaking, this translates into lesson plans where educational and/or behavioral objectives are clearly stated, with input material and strategies devised to ensure the meeting of objectives. The underlying metaphor is also indicated by the predominance of such concerns as "efficiency" and "maximization," and the reliance on "objective tests" to determine whether the information processing was successful.

Faith in this similarity of computers and brains has also led to the utilization of computers as teachers, able to instruct students without the contaminating influences of teacher bias or emotion. Similarly, "context free" teaching has found adherents, particularly in "skill areas." Examples are provided by some "thinking strategy" or "creative problem solving" programs (see above) which are based on the premise that by learning certain algorithms one can tackle any problem, regardless of context. Another example is provided by the teaching of outlining as a technique guaranteed to produce superior papers. While some writers may find extensive outlining helpful, many find outlining too restricting, hampering the generation of ideas and the flow of writing. Asked to turn in an outline along with a paper, many students find themselves composing the outline after the paper is finished. While it is certainly possible to school oneself to think in logical outlines or flow charts (computer programmers are clearly expert in this skill) the formation of the flow chart probably follows the real mental processing, which is a much more parallel, nonlinear, and frequently chaotic process.

The Impact of a Nonlinear View of the Brain

Many scientists now studying nonlinear dynamic systems believe that we are currently on the leading edge of a paradigm shift, a shift away from the old, linear, mechanistic point of view (see Gleick, 1987). Researchers in almost every discipline are studying nonlinear dynamics, and this will lead to new understandings of fundamental processes. Paradigm shifts do not happen instantly. There are always intimations that a change is "in the air," and, equally, there are always artifacts of the older paradigm that persist despite the change. Presently, thanks to authors such as James Gleick, ordinary people are beginning to hear about nonlinear dynamics, and they are beginning to understand and celebrate complexity. We are outgrowing our old metaphors. If we need another metaphor for brain function, it will probably be the computer neural network. But perhaps complex nonlinear dynamics will allow us to grow beyond metaphors, at least for describing brain function. We will be able to say that the brain is a chaotic, nonlinear dynamic system, rather than saying the brain is like a machine, a computer, or a neural net.

As nonlinear mental models are proposed and accepted, we will find ways to capitalize on our ability to process in parallel. This paradigm shift could have profound educational consequences, the extent of which has only been hinted at here. Currently, the insistence on controlling input so as to ensure the quality of output discourages the free exploration that results in disequilibrium. Without allowing disequilibrium and far-from-equilibrium states, creativity and the possibility for innovation is seriously hampered.

Part of the desire to rigorously control input arises from reluctance to let children "get in over their heads," and risk failure. Educational strategies such as Barbara Clark's integrated learning (Clark, 1988) which stress exploration and immersion in new areas of interest, and which decrease or eliminate penalties for imperfection, should allow students to become comfortable with disequilibrium.

The new paradigm will prize disequilibrium as the catalyst of creativity, and students will be allowed to range further. Educators, administrators and legislators will come to understand that humans, as nonlinear dynamic systems, are not predictable, and that creative production is not something that can be determined by application of the right "recipe."

Finally, nonlinear dynamics may eventually be taught in schools. Widespread knowledge of chaotic complex systems will foster a new understanding of the fragility of our environment, and an appreciation of the interdependence of all biological systems. Ideally, an understanding of nonlinear dynamics will revolutionize our understanding of the world at large and could free us of linear-sequential paradigms that are currently proving more and more limiting.

CHAPTER VI

SUMMARY, LIMITATIONS, FUTURE DIRECTIONS, AND CONCLUDING REMARKS

Summary

At a recent gathering of scholars interested in creating a unified theory of optimal human development (see Ambrose, 1992), much energy was expended by participants arguing about the nature of creativity. The core of the dispute centered around whether the mundane insights and little revelations such as we all experience could be considered creative, or whether true creativity was limited to the world-shaking, field-revolutionizing work of a handful of geniuses.

The difficulty with adopting the view that creativity is the exclusive domain of genius is that someone, or some group, must make a judgment regarding whether an idea or product is creative. All such judgments are subjective, and many are in error. This is amply illustrated by the individuals who are now accepted as geniuses, but were not acknowledged in their own time. If creativity manifests only when a person's work is valued by others, then individuals such as Emily Dickenson did not become creative until after they died.

In contrast to this elitist view, this dissertation takes the position that creativity is a universal human phenomenon. It arises naturally from the nonlinear dynamics of the complex, highly nonlinear, human being, both at the level of neuronal function (as discussed in Chapter III) and of cognitive experience (see Chapter IV). The proposal made here is that when individuals allow themselves (or in some instances are pushed) to experience a far-from-equilibrium state, they become extraordinarily sensitive to changes in internal or external factors. In this state, the influence of even the most minute nuance of an experience can cause a fluctuation which invades the system and induces it to self-organize to a new level.

If the newly attained level is unstable, if it is also far-from-equilibrium, then the individual remains exquisitely sensitive and the creative process can continue. If, on the other hand, the new level is stable, if, for example, one arrives at the undisputed answer to a problem, then one has attained a new equilibrium. Once equilibrium is reached, the process stops, at least until the individual again experiences the far-from-equilibrium state.

This perspective does not rule out creative experience occurring during an equilibrium state. It only suggests that the energy needed to overcome the equilibrium constraints would be far greater, and consequently the probability of creative response would be less.

Simply put, the view proposed here is that creativity arises at the most fundamental level as a cortical brain function. This means that everyone has the capability to be creative. Whether creativity is experienced and expressed depends with infinite sensitivity upon the ability of individuals to tolerate or seek out far-from-equilibrium experience, the openness with which they meet it, and the intellectual, emotional, and experiential resources they bring to that experience.

A natural corollary to this proposal is that an individual's creativity can be nurtured and enhanced. It can also be discouraged and destroyed. Educational settings in which nonequilibrium exploration is accompanied by high levels of risk and in which nonconformity is discouraged will not nurture students' creativity. In contrast, environments which are perceived as safe and tolerant of such exploration, and in which individual differences are celebrated, are more likely to elicit creative responses.

Limitations of This Study

Every study is subject to limitations, and this one had several that influenced its scope and depth. The first and perhaps most profound limitation was that of insufficient time. The sudden and unexpected decision to close the University of Oregon's Division of Teacher Education severely limited the amount of time I could spend on this study. Secondly, my dissertation committee requested that this dissertation be written such that it could be understood by readers unfamiliar with nonlinear chaotic dynamics and neuroscience. Both of these areas are extremely complex, and in order to comply with the committee's charge, I had to simplify, interpret, and translate much of the material. Also, in the effort to maintain a tight focus, I had to forego discussion of much interesting and related information. Readers interested in greater depth and precision are urged to refer to the books listed in the Reference section of this dissertation.

The third limitation is imposed by the philosophical underpinnings. This study is founded in materialistic realism, and is therefore subject to all of the shortcomings of this philosophy. Materialistic realism asserts that matter is fundamental, and that consciousness arises as an emergent quality resulting from the interactions of the material that composes the brain (see Goswami, in press). In other words, everything we experience as consciousness, such as thought, emotion, and sense-of-self, can be reduced to the myriad electrochemical interactions of neurons. Confronted with such a proposition, many will protest, "There must be something more! How can a bunch of molecules become self-aware?" Defining consciousness within the materialistic philosophy is difficult.

Unique Advantages of This Perspective

There are two aspects of nonlinear dynamic systems that are particularly appealing. The first is that nonlinear dynamic systems demonstrate scaling. This refers to the similarity of structure or function that such systems exhibit, regardless of the level of description employed. Structural similarity is demonstrated in fractals (see Chapter II). The similarity of shape of a tree, a branch, a twiglet, and the veins of a leaf is one example. Nature abounds with examples of fractals.

Behavioral similarity is demonstrated in the nonlinear perspective of human creativity. The description of the creative process presented in Chapter IV has the same explanatory power whether one is talking about the creation of new information on a neuronal level, on the level of an individual, or a group of individuals. Each level can be viewed as a nonlinear system which, when pushed far-from-equilibrium, becomes extraordinarily sensitive to changes in variables and can spontaneously and abruptly self-organize to a new level. By extension, such a description can be used to describe the creativity of a culture, and even of the entire human species.

The second intriguing aspect, and perhaps the most compelling reason to pursue a nonlinear dynamic description of the creative process, is that in doing so we may link human creativity to universal creative processes. Frank Barron once said:

> I think of it [creativity] as something that is happening in the central nervous system. My own basic interest in research in creativity stems from the hope it offers that one may find in psychic creation the same formal variables that can be used to describe creative process in all of nature. (Barron, cited in Taylor, 1988, p. 106)

The description of the creative process presented here can offer such a hope, for it can even be extended beyond the scope of human creativity to include universal creative processes. For example, Crutchfield et al. (1986) state:

> Nature may, however, employ chaos constructively. Through amplification of small fluctuations it can provide natural systems with access to novelty. . . . Biological evolution demands genetic variability; chaos provides a means of structuring random changes, thereby providing the possibility of putting variability under evolutionary control. (pp. 56-57)

Nicolis and Prigogine (1989) find creative processes in simple, albeit nonlinear, chemical and mechanical systems: "Such ordinary systems as a layer of fluid or a mixture of chemical products can generate, under certain conditions, self-organization phenomena at a macroscopic scale in the form of spatial patterns or temporal rhythms" (p. 8). Most strikingly, recent discoveries by astrophysicist George Smoot suggest that nonlinear, nonequilibrium chaotic dynamics were at work during and after the Big Bang, resulting in an inhomogeneous universe and the birth of galaxies (Register Guard, 24 April 1992, pp. 1a, 4a). If the perspective on the human creative process presented in this dissertation is valid, then its explanatory power and its advantage over other theories of creativity is enhanced by this relationship to universal creative processes.

Scientists have striven for centuries to find the simple, underlying forces that can explain all of nature. An understanding of nonlinear, nonequilibrium dynamics suggests that perhaps there are universal underlying forces, but they are not simple (Briggs & Peat, 1989; Gleick, 1987). Perhaps the nonlinear "rules" governing the creation of the universe or the evolution of a snowflake are the same as those governing the creation of a symphony, and in that sameness there is a kind of simplicity. But the processes themselves are highly complex.

Unanswered Questions and Possibilities For Future Investigation

Since the study of nonlinear dynamic systems is relatively new, the possibilities for future research are unlimited. There are several questions, however, which are suggested by this study, and which may be worthy of further investigation.

1. Many theorists agree that purpose is a necessary (though not sufficient) condition for high level creativity (see, for example, Amabile, 1989; Gruber, 1988; Rostan, 1991). From a nonlinear perspective, the importance and influence of purpose on creative efforts is easily explained. Few would argue that human beings have the capability of imagining future events, and, if the event is desirable, working to help bring it about. For example, a young boy may envision obtaining a special game. If his parents refuse to buy it for him, he can decide to work until he has enough money to purchase it. In other words, his desire for the game and his decision about how to obtain it become constraints upon his present behavior. If the constraints are sufficiently strong, and if the other constraints on his behavior, such as the availability of work for which he can get paid, do not interfere, he will most likely succeed in reaching his goal. What is not explained

by the nonlinear perspective is how "purpose" (a cognitive state) exists as a brain state.

2. The underlying issue, the answer to which will clear up many questions regarding the nature of mental activity, is whether mind and brain are the same entity, or whether the brain is merely the material organ upon which a transcendent mind plays. If they are the same, then presumably a particular brain state will correlate with a particular cognitive state. At this time, such a correlation has not been found. It might be fruitful, as a first step, to try to establish a link between the state of the brain during a creative moment and the conscious recognition of having a novel thought. This might be done through obtaining electroencephalographic (EEG) or brain mapping recordings made while a subject was experiencing a creative moment. Using techniques similar to those of Skarda and Freeman (1987), one could try to isolate a strange attractor from those recordings and determine whether it differs from the attractor evident prior to the creative moment.

Of particular interest might be the dimensionality of the new attractor. If it were of higher dimension, indicating more complex behavior and more degrees of freedom, such an attractor might suggest that the brain is indeed experiencing chaotic dynamics as it creates new ideas.

The difficulties inherent in this proposed experimental protocol may prove insurmountable. In the first place, since creative moments are unpredictable, it would be difficult to engineer a situation in which such a moment might be captured on EEG. One possibility would be to use some problem-solving exercise as a means for eliciting a creative response. Unfortunately, such exercises usually require activities such as reading, writing, or drawing, which would cause muscle artifacts on the EEG tracing, thus masking other electrical activity. This difficulty could be overcome if some activity were devised which was wholly mental. Another difficulty is posed by the need for the subject to somehow indicate that a creative thought has or is occurring, so that the EEG tracing could be marked.

3. Whether or not the mind and brain are synonymous, on a purely physical level, some questions can be raised regarding nonlinearity and the brain. The discussion in Chapter III was largely limited to cortical structures. The question remains whether every brain structure is a nonlinear system. The case was made in Chapter III that nerve cells themselves function as nonlinear systems. Does this nonlinearity carry through into all higher structures? Are the more primitive parts of the brain, such as those that regulate vital functions like respiration and heart rate,

also nonlinear? If so, does this nonlinearity shed new light on our understanding of brain dynamics?

4. As noted in Chapter III, Goldberger and West (1987) speculate that fractal architecture of physiological structures serves to increase the efficiency of function of that structure. Extending their argument, one can speculate that the fractal structure in the cortex serves to support nonlinear dynamics by increasing the density of neural connections. An interesting question is whether the fractal architecture is an artifact of the play of nonlinear dynamics. Do the particular branchings of dendrites occur in response to nonlinear sensitivity to changes in variables, such as those introduced by stimulation of the system? Are the occurrences truly random, or are they purely driven by genetic instructions?

5. The proposed model for the creative process presented in Chapter IV suggests that when a nonlinear system is driven far-from-equilibrium, it may abruptly self-organize to a higher level of organization, one which contains more information than the previous level. Such a description sounds much like a description of the learning process. The question arises: Is all learning a creative process? Where do we draw the line between simple learning and creativity?

6. Freeman (1991) has suggested that memories exist in the brain as basins of attraction (see Chapter III). This is an intriguing idea which warrants further investigation. If his ideas are supported by evidence, they may have interesting implications for educational practice. If memories exist as basins of attraction, this may explain why unlearning a concept or "fact" can be so difficult, since energy is required to escape from the confines of a basin.

7. In the area of education, questions naturally evoked by this study have to do with how exactly the nonlinear dynamic model could be incorporated into educational practice. Clearly, investigations are needed into the idea of allowing students to depart from equilibrium. In particular, these need to focus on the correlation between distance from equilibrium and creative ideation. Other studies could be done regarding the effects of far-from-equilibrium exploration on such factors as self-esteem and motivation. Studies are needed of the efficacy of using paradox, controversy, riddles, and interdisciplinary study to encourage students to break through their conceptual boundaries. Similarly, studies are needed of the correlation between risk-free exploration and creativity. New instruments need to be developed for detecting creative capability, perhaps focusing on tolerance for far-from-equilibrium states and sensitivity to small changes and situational nuances.

Concluding Remarks

This dissertation is not conventional. Many readers may feel it wanders so far from the beaten paths of educational research that it is without value. However, as demonstrated by the ant species Tetramorium, sometimes new trails lead to rich sources of ideas and information. With no guarantees that the trail will prove fruitful, the risk represented by such an exploration is great. If, however, the ideas presented here serve to further discussion in the areas of creativity theory, brain function, or educational strategies, then the effort has been worthwhile.

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