THE RECATHERORIZATION OF "CHAOS":
A CASE STUDY OF LANGUAGE CHANGE AND THEORY CHANGE

by

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(ABSTRACT)

This thesis investigates the relationship between semantic change and theory change in science. The study focuses on thirty years of developments in chaos theory. Because of measurement problems associated with certain nonlinear phenomena, the observability of chaotic systems is severely limited. In such cases, ongoing processes of language change may play a greater role in shaping scientific theories than in cases in which the phenomena are more easily observed. This study is interdisciplinary, drawing on theories from linguistics, philosophy, philology, and sociology. Several mechanisms of semantic change are explored in order to discover their possible influence on theory formation. Developments in chaos theory are described in terms of George Lakoff's radial model of conceptual categories. This model describes concepts in terms of (1) a central cluster which acts as a prototypical example, and (2) various non-central extensions from that center. I argue that in an emerging discipline, non-central extensions are made depending on the interests of the community. As Andrew Pickering observed, communities on the research front select a research direction that will "intersect with the interests" of more established research communities. This thesis explores several examples of historical developments in chaos research showing how conceptual change in science can be described in terms of Lakoff's radial category model and Pickering's interest model.
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CHAPTER ONE: A Background on Chaos

SECTION I. Introduction

The purpose of this thesis is to investigate interactions between language change and theory change in the emerging field of chaos theory. I argue that a model of conceptual categories similar to that discussed by George Lakoff in his 1987 book, Women, Fire, and Dangerous Things, explains many important developments in theories about chaos. The choice of chaos theory as a subject for the case study was inspired by the observation that journal articles related to "chaos theory" contained patterns of language usage that would be considered paradoxical or oxymoronic if assigned conventional meanings. A survey of articles published in scientific journals indicates that the seemingly paradoxical language used by scientists and mathematicians is the result of a thirty year period of rapid semantic change in several different scientific circles.

This thesis investigates the nature of theory change in terms of two interrelated questions: one concerns the extent to which theory changes are driven by mechanisms of language change, and, the other, conversely, concerns the extent to which language changes are influenced by a given theoretical framework.

These questions fall within several traditions investigating the nature of conceptual change. The discussion
in this thesis owes much to ordinary language philosophy, as well as to structuralist linguistics. However, criticisms of these traditions have pointed to a need for an interdisciplinary study in which the strengths of different approaches can be combined to overcome some of the deficiencies.

For example, in his introduction to *The Linguistic Turn*, Richard Rorty argued that the analytic tradition had become too narrow, failing to answer many important questions about changes in meanings and senses (Rorty, 1967). Roman Jakobson criticized Saussurian structuralism, in part, because it offered no account of the relationship between signs and objects in the world. He felt that this relationship was addressed by C. S. Peirce's theory of pragmatism (Jakobson, 1980). Thus, partly as an extension of developments in the tradition of pragmatism, this thesis emphasizes the relationship of language not only to theories and denotata, but also to its human users. The relationship of language to its users is explored, here, in light of both cognitive and social factors.

Chapter One provides a brief history of the development of chaos theory, explaining how measurement problems connected with certain nonlinear systems often force scientists to explore ways other than direct observation in order to develop a conceptualization of "chaos."
Chapter Two provides a background on linguistics and ordinary language philosophy. In this discussion, I outline some basic principles and criticisms of structuralist linguistics and of pragmatism. I also describe Lakoff’s radial category model. Lakoff’s model takes into account the complex relationships among words, objects, events, conceptual frameworks, and communities.

In subsequent chapters, I develop a variation of Lakoff’s radial model, drawing on a number of theories from philosophy and linguistics. In Chapter Three, I analyze the technical vocabulary of chaos theory in terms of the background theory presented in chapter two, explaining how a central cluster of a radial model is created. This central conceptual category characterizes the phenomenon of chaos in terms of typical examples, and it is perceived as quite distinct from categories corresponding to other, non-chaotic, phenomena.

In Chapter Four, I discuss Lakoff’s radial model in terms of conceptual changes motivated by interests. Drawing on Andrew Pickering’s essay, "Interests and Analogies," I show how scientists studying chaos link their work at the research front to established traditions in other fields by creating non-central extensions from the central cluster of the radial model.

Due to complications that nonlinear dynamical systems pose on empirical methods, the study of chaos is an area in which words and expressions seem to vary widely in their
reference to denotata. While there is no privileged point of reference from which to judge terms as being more or less accurately representative of nature, there is greater agreement among scientists as to the sharpness of a category, and greater consistency in their use of terms associated with that category when they manipulate objects in ways that are most natural to human beings.

Those studying complex chaotic phenomena have found that access to the "real world" by way of conventional scientific methods, such as measurement and quantitative prediction is particularly difficult because of the effect that certain types of nonlinear equations have on computations of experimental error. In response to this problem, many scientists have shifted their focus away from direct empirical investigations of specific real-world phenomena. The trend is to employ alternative techniques, such as creating computer models of idealized natural phenomena, constructing geometrical and topographical descriptions of very general or "global" behavior of entire families of functions, developing qualitative descriptions and verbal arguments, and using analogical reasoning. A more detailed discussion of the measurement problem in "chaos theory" will be presented in this chapter shortly.

Linguistic influences on theory changes related to the study of chaos cannot be fully appreciated without a general understanding of the technical terms as they are used by those
working in related mathematical and scientific disciplines. A general understanding of chaos is best approached through a brief history of developments that contributed to scientists' current work in chaos theory.

SECTION II. Early History of Chaos

Although the term "chaos" first entered the English language during the Middle English period (1100-1500), its technical usage in physics started in the twentieth century (Pyles and Algeo, 1982:297; Pool, 1989b:26). This more recent sense of the word "chaos" was introduced by Jim Yorke in 1975.¹ In his article "Period Three Implies Chaos," he used the term "chaotic" to refer to a nonperiodic sequence of iterates of an equation (Li and Yorke, 1975:986).²

The equations that Yorke was referring to are a special type of dynamical system. Dynamical systems are those that change their state with time (Stewart, 1989:42). In systems that change with time, the output feeds back and affects the next input. One way to create a dynamical system is to take a function, as Yorke did, and iterate it. That is, given an initial value, and some function of x, take the initial value and substitute it into the variable x. Then take the output

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¹Yorke works at the Institute for Fluid Dynamics and Applied Mathematics at the University of Maryland.

²A more detailed analysis of the word "chaos," related terms, and their extensions is presented in Chapter Three.
of the function and feed it back into the same function as the new input value. Now take the new output value, and, again, use it as the next input value. If this is done repeatedly, then a series of outputs for the iterated equation is obtained: $x, f(x), f(f(x)), f(f(f(x)))$, and so on. Depending on the function that is iterated, the sequence of iterates can behave in different ways. For instance, the values for $x, f(x), f(f(x))$ ... could just keep increasing. On the other hand, the values might converge to some limit (Devaney, 1989:2; Hofstadter, 1981:24). Another possibility is that the values might oscillate periodically. Finally, a non-periodic fluctuation of values can be obtained from the iteration process. The non-periodic behavior is what Yorke called "chaotic."

The interesting thing about those particular dynamical systems that produce complex behavior, such as a random sequence of iterates, is that the equations themselves are deterministic, and often quite simple. So it is possible to obtain random behavior from very simple deterministic equations. Thus, scientists and mathematicians often describe chaos using the oxymoron "deterministic randomness" (Pool, 1989a:25).

The language of chaos theory often sounds like some sort of double-speak because of the striking number of oxymorons one encounters. These oxymorons are one indicator of the interdisciplinary origins of chaos theory; they are, in part,
the result of the intermingling of technical terms associated with a number of diverse scientific traditions. For instance, since the equations known to produce chaotic behavior are often found in the area of classical dynamics, much of the vocabulary of chaos theory contains terms referring to determinism, order, and stability. On the other hand, since the output of the classical equations is erratic, the terms describing the fluctuating output are often drawn from probability theory and thermodynamics. Thus one finds discussion of "stochastic properties," "entropy," and "randomness," strangely juxtaposed with the vocabulary of "order" and "determinism." The existence of the oxymorons points to the historical emergence of chaos theory from the fringes of quite different traditions in science.\(^3\)

The discovery that simple deterministic equations can produce complicated or even random behavior led many mathematicians to wonder whether complex and erratic phenomena in nature could be predicted with dynamical systems models. Li and Yorke's study of the behavior of iterated equations was influenced by the work of Edward Lorenz of MIT, who in the early 1960s had used dynamical systems to model fluid flow and weather patterns. Lorenz had been conducting a numerical experiment modeling an atmospheric system when he accidentally

\(^3\)For several accounts of the emergence of chaos theory as an interdisciplinary field, see Bishop (1990), Chernikov et al. (1988), Edelson (1986), and Percival (1989).
discovered one of the properties of what Yorke was later to call "chaos." Lorenz was using iterated dynamical equations to produce a sequence of values that modeled Rayleigh-Bénard convection in air flow. At one point, he decided to reproduce a sequence that he had obtained before but with a longer run on the computer. Since he was primarily interested in the later behavior, he decided to save time by typing in an intermediate value from the data printout, rather than starting the whole sequence over with the original value. Lorenz naturally expected results identical to the part of the original sequence that followed this intermediate value. Surprisingly, however, the new sequence followed the old one only for a short time before it started to diverge. Soon the new sequence looked nothing at all like the old one. Lorenz realized that when he had typed in the intermediate value from the printout, he had used only three digits (only three were shown on the printout, but six were actually stored in the computer's memory). The small difference between the original stored value and the rounded value typed in from the printout had produced the striking divergent behavior in the two computer runs (Gleick, 1987:16-17).

SECTION III. Sensitivity to Initial Conditions (STIC)

The tendency for certain dynamical systems to respond very differently to small differences in input (as demonstrated by Lorenz' two computer runs) is commonly used as
a rough definition of chaos. However, the ability to identify systems as chaotic does not lead to any great predictive power. On the contrary, the property "sensitivity to initial conditions" (hereafter, STIC), places severe limits on the predictability of the long-term behavior of a dynamical system. Nevertheless, it is useful to know the limits of predictability.

In principle, it should be possible to predict the behavior of chaotic systems, since the equations are deterministic in the sense that the input causally affects the output. The eighteenth-century mathematician Pierre Simon Laplace had viewed the universe as completely predictable once the position and velocity of all its particles were known. And, in fact, if the position and velocity of even a chaotic system were known exactly, then one could predict the behavior of that system. Similarly, if Lorenz had started his two computer runs with identical initial values, then he would have obtained exactly the same series of fluctuations in both runs. The output of the equations is entirely determined by the mathematics, which explains the origin of the strange description "deterministic chaos."

"Currently there exist a number of different definitions closely related to the general property of "sensitivity to initial conditions." D. S. Ornstein, a professor of mathematics at Stanford University, observes that "there is no agreed upon definition of 'chaotic' in the literature on chaos ..." (Ornstein, 1989:183). Those interested in comparing definitions of the word "chaos" are referred to Procaccia (1988), Devaney (1987), and Khurana (1988)."
Nevertheless, in reality, all measurements, no matter how carefully done, are accompanied by some degree of uncertainty, which makes Laplace's dream of total predictability impossible (Crutchfield, et al., 1986:46, 48). Since the output is not proportional to the input in many nonlinear dynamical systems, a small degree of uncertainty in a measured value grows over time. Thus, one cannot simply carry the computations of experimental error through to the results and still expect to obtain an approximation with a reasonable margin of error, as is done in predictions of linear phenomena (Percival, 1989:42). The concept of STIC had been stated in 1903 by Henri Poincaré who studied nonlinear differential equations using the qualitative methods of topology and geometry (Crutchfield, et. al., 1986:46, 48; Devaney, 1989:viii).\(^5\)

SECTION IV. Qualitative Methods of Studying Chaos

How then, does one study nonlinear dynamical systems if one cannot make predictions over a substantial length of time? In response to this difficulty in making predictions, those studying chaotic systems tend to look at the "global

\(^5\)In 1903 Henri Poincaré described what we now call "sensitivity to initial conditions." He observed that: "...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" (Quoted from Science and Method in the Preface to the collected papers from The Second Annual International Conference of the Center for Nonlinear Studies, Los Alamos, May 24-28, 1982, in Physica 7D, 1983).
properties" of a system of equations, that is, to look at the full range of possible solutions to a system, rather than to predict the local behavior of the system for some particular value (Devaney, 1989:viii; Smale, 1967:747; Gleick, 1987:46–47). Trying to predict the outcome from a particular measured starting value is doomed to fail because of STIC. But running many values allows one to see what kind of behavior is characteristic of a particular system. Because of the measurement problem, then, much of the work being done in chaos theory is an attempt to discover the global properties of dynamical systems and to classify systems based on these properties. This approach to mathematics is called the qualitative theory of differential equations.

For instance, in very difficult cases, traditional tools used in celestial mechanics are now being set aside in favor of a more qualitative approach that focuses on the global behavior of dynamical systems. Although Laplace’s work on the N-body problem in the eighteenth century included a "proof" that the solar system is stable (W. W. R. Ball, 1960:414), that proof has since been shown to be unrigorous. Poincaré, for instance, proved that the expansion of solutions to the N-body problem into an infinite series results in a series that is not convergent. Also, recent computer experiments modeling the universe suggest that the interactive behavior of the planets in the solar system results in trajectories that are not convergent. In fact, the trajectories diverge
exponentially (due to STIC), a behavior that characterizes chaotic systems (Rothman, 1988:20; Laskar, 1989:237; Milani, 1989:207). Because the dynamics of the solar system is chaotic, J. Laskar of the Bureau des Longitudes notes that:

the traditional tools of quantitative celestial mechanics (numerical integrations or analytical theories), which aim at unique solutions from given initial conditions, will fail to predict [the orbits of planets.] The problem of the stability of the Solar System will have to be set up again, and the qualitative methods initiated by Poincaré definitely need to replace quantitative methods in this analysis (Laskar, 1989:237).

Often graphical techniques are used to explore the global behavior of a system. Difference equations are used as models of population dynamics, or as models of economic cycles, but instead of merely obtaining a sequence of iterates of an equation in numerical form, the successive values for \( x \) and \( y \) can be seen by plotting a return map. To prepare for mapping, one plots the graph of the original function on an \( x, y \) axis. The function must be one that has a graph that is folded, i.e. one that has one or more humps. A point is called a fixed point when the input of an iterated equation is equal to the output, indicated by \( x = f(x) \), or equivalently, \( x = y \). By construction then, fixed points can be found geometrically by superimposing the line \( x = y \) (a 45 degree line) onto the graph of the function. The locations where the graph of the function and the graph of the line \( x = y \) intersect indicate the fixed points.
Fixed points can either be stable or unstable; they are either **attractors** or **repellers** depending on the slope of the tangent line at the intersection of the graph with the line $x = y$. If the upward or downward slope of the tangent line at the fixed point is less than or equal to 45 degrees, then the fixed point is stable (an attractor). If the slope is greater than 45 degrees, then the fixed point is unstable (a repeller) (Hofstadter, 1981).

The map itself consists of a series of geometrical projections from the function graph, to the $x = y$ line, and back to the function graph again. Using this construction technique repeatedly, one can then obtain a visual representation of the behavior of an iterated function. For example, if the function is one that produces a series of iterates that converge to a single value, the pattern produced by the mapping technique spirals inward, terminating at the fixed point. Since the graph moves **toward** the fixed point it is called a fixed point **attractor** (Hofstadter, 1981).

Alternatively, if the function is one that produces iterates that at first increase, but eventually end up oscillating between two values, the map spirals out from the fixed point until it intersects the function graph at one of the values repeated during oscillation. After intersecting the graph, the map repeatedly loops in a square. The two corners of the square that intersect the graph have $x$ coordinates corresponding to the two values that are repeated
during oscillation. In contrast to the first example, the map moves away from the fixed point, and so that point is unstable, or a repeller. However, the x coordinates of the two corners of the square loop constitute what is called an attractor of period two. Similarly, a map can have an attractor of period four. However, the loop in this case is more complicated than a simple square because four of its corners intersect with the graph of the function. The x coordinates of the points at the corners of intersection constitute an attractor of period four. Maps can have attractors of other values also (Hofstadter, 1981). See figure 1.

The patterns produced by mapping the iterates of a function are called orbits. If the graph has either a fixed point attractor, or a periodic attractor, then for different initial or seed values for x, the same orbit will be reproduced each time for each type of graph. See figure 2. The behavior of these maps is stable. Because of this regularity, systems that are represented by logistic equations are classified according the type of orbit they produce (Hofstadter, 1981).

The type of orbit produced does not depend on the seed values for x. Instead, it depends on a parameter measuring the height of the hump on the folded graph. If the function has a relatively low hump, the slope of the tangent line at the fixed point is less than 45 degrees, and so the fixed
Figure 1. Return Maps Showing Different Attractors. As the Parameter is raised, the period of the orbit doubles and each attractor splits into two attractors. Also, the distance between the attractors decreases, producing a Cantor set pattern (See also figure 4). Produced on Phaser.
Figure 2. Return Maps Demonstrating Stability. If the parameter is below the critical value, then identical orbits will be produced from different initial (or seed) values. A system is stable if different initial conditions produce the same orbit. Produced on Phaser.
point is an attractor. The orbit of any seed converges to the fixed point attractor. If the hump of the function is raised enough, then the slope of the fixed point is greater than 45 degrees, and so the fixed point is a repeller. In this case the graph has an attractor of some period instead of a fixed point attractor.

In general, as the parameter (or height of the hump) is increased, the fixed point attractor becomes a repeller and **bifurcates**, resulting in a stage at which the attractor is of period two, then a stage at which the attractor is of period four, then period eight, and so on. Each attracting point, in turn, becomes a repeller, as the parameter (or hump) is raised. The higher the parameter is, the higher the period of the attractor will be, and the periods double at distinct values of this parameter (Hofstadter, 1981). Refer to figure 1.

However, not all graphs produce periodic orbits; they can produce non-periodic orbits if the hump is high enough. Beyond a certain critical value for the height parameter, different seeds for x values no longer produce mappings that converge to a definite characteristic orbit. Although some seed values produce periodic orbits, these orbits have such a long period that it is hard to tell that there is any pattern. Other seed values may produce non-periodic orbits. But the important characteristic of the behavior of functions with a parameter at or beyond the critical value is the tendency for
orbits to diverge. The behavior beyond the critical value for the parameter is called the chaotic regime because of this property of divergence. Divergence or STIC is demonstrated by plotting two return maps for a function that has a value for the height parameter at, or beyond, the critical value. Starting from any two seeds, however close together, after several iterations, the mappings become very different. See figure 3. The attractor that produces such diverging orbits is called a strange attractor, and it consists of an infinite number of points (Hofstadter, 1981:43). The x coordinates of the points on a strange attractor are distributed on the axis in a pattern resembling the scaling properties of a Cantor set. See figure 4. "Scaling" means that the distance between the x coordinates of the bifurcating fixed points decreases by some constant value as the period-doubling parameter is raised. Note the Cantor set pattern of the attractors in figure 1. Because of the decrease, the range that the points cover remains bounded even though they split or bifurcate infinitely many times at the critical parameter value. It is like an infinite series that converges to a limit (Hofstadter, 1981: 31, 42-43; Gleick, 1987:45-52). For our purposes, it is sufficient to know that the Cantor set has a pattern that is easily recognizable, and which is used to classify visual representations of systems. Mappings or plots in phase space that have a strange attractor exhibit this characteristic scaling pattern.
Figure 3. Return Maps Demonstrating Chaos. If the parameter is at, or above the critical value, then different initial conditions produce different orbits. Even a small difference in the initial conditions results in very different maps. In this figure, the initial conditions differ by only 0.0001, but the maps are quite different. This is called sensitivity to initial conditions (STIC). Produced on Phaser.
Figure 4. The Cantor Set. The Cantor set is a geometrical pattern produced by repeatedly removing the middle third of line segments produced by the previous step. Note that each time this is done, one obtains two scaled-down versions of the original line segment. This self-similar pattern can be seen in mappings and phase portraits of chaotic systems. See figures 1, & 10. Redrawn from Gleick 1987, p. 93.
Plots in phase space are similar to mappings in that they are used to represent the behavior of dynamical systems in terms of their periodic or non-periodic behavior. As in mappings, one discusses orbits of different periods and also nonperiodic orbits. See figure 5. Representations of systems in phase space differ from mappings in that mappings represent discrete systems, while trajectories in phase space represent the continuous variation of the state of a system. Trajectories in phase space are usually plotted in terms of a system’s changing position and velocity.6

Because of the STIC problem, work in chaotic dynamical systems has typically concentrated on creating models that reveal the general characteristics and mathematical properties of such systems. These general characteristics are then used to categorize phenomena. In the early seventies, the focus was on distinguishing the chaotic behavior of systems from other phenomena that produced random fluctuations. For instance, the biologist Robert May investigated logistic difference equation models of animal population systems by using return maps. May was influenced by the work of Lorenz, and also that of Yorke and Li, and was struck by the fact that simple dynamical equations could produce complex behavior. When May investigated the behavior of population dynamics models, he found it "remarkable and disturbing" that "the

6See Stewart (1989) for a more detailed discussion of phase space.
Figure 5. Trajectories in Phase Space. As with return maps, phase space diagrams can have fixed point attractors, periodic attractors, or strange attractors. This diagram shows a strange attractor. The phase space containing the attractor is stretched, resulting in the exponential divergence of trajectories (a). This is the mechanism for STIC. The space is also folded, resulting in trajectories that are bounded (b). Adapted from Crutchfield, Farmer, Packard, and Shaw 1986, p. 51.
simplest, purely deterministic, single species models give essentially arbitrary dynamical behavior once \( \mathcal{r} \) is big enough" and that "the dynamics of populations with 'density dependent' regulation could nonetheless in some circumstances be indistinguishable from chaos, if the intrinsic growth rate \( \mathcal{r} \) were large enough."

May realized that the erratic behavior of the model was determined by, or "latent" in the model itself. That is, the randomness was shown to be a property of the mathematics. This property made him realize the futility of trying to use such models to make predictions about the real world until the mathematics of the models themselves were understood. He recognized that first there must be detailed investigations into the range of behaviors that the mathematics could produce on their own (i.e., without the introduction of factors external to the model, such as experimental error) (May, 1974:645, 647).

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'May's use of the phrase "indistinguishable from chaos," is interesting since the deterministic randomness he was describing is what is now defined as chaos (May, 1974:645). The usage of the word had apparently not stabilized yet, although in the same article May had noted Yorke's application of the word "chaotic" to sequences of iterates that are aperiodic. The reason for this is probably because Li and Yorke's classic paper, "Period Three Implies Chaos," was still in press. After December, 1975, when Li and Yorke had established their definition of "chaotic" in print, the term was used, more or less consistently throughout the nineteen seventies. Nevertheless, the terms "chaos," and "chaotic" seemed to acquire a number of variant meanings in the nineteen eighties.
Thus, in May's studies, the models were not used to make specific predictions about actual populations in the world. Rather, they were used to show what general characteristics are determined solely by the mathematics for different initial conditions and different values for the growth rate parameter. The nonperiodic orbits produced by these models were then compared and contrasted to other factors that produce fluctuations, such as environmental "noise," and experimental errors in sampling or measurement (May and Oster, 1976:573, 583, 585).

SECTION V. Summary

First, despite a heavy theoretical emphasis, the study of chaos is not restricted to the manipulation of abstract mathematical models. The STIC problem limits quantitative predictive power in many situations, but does not rule out observation. The role of prediction in science is often seen as primary, but prediction is only one type of link used to establish a connection between theory and observation. The study of chaos reveals the many alternative conceptual resources available to scientists. Second, although STIC rules out accurate long-term predictions about the population of fish at a particular time, or the exact motion of a planet in space, or the velocity of a specific particle in a fluid, it is possible to measure and observe certain global regularities in a physical system.
A third way of getting around the STIC problem is to focus on the behavior of a physical system that occurs before the onset of chaos. Much of the experimental work involves the investigation of what happens at the boundary between periodic behavior and nonperiodic behavior. Systems are then classified according to behavior leading up to the onset of chaos.

Much of the work in fluid dynamics makes use of these three ways of getting around the STIC problem. First, there is a greater dependence on links between theory and experiment that do not rely exclusively on prediction. Instead, analogies are drawn from areas of study in which prediction is easier, to areas of study where it is more difficult (The use of analogies is discussed in Chapter Four). Second, scientists avoid attempts to predict specific temperatures and velocities in favor of alternative methods, such as measuring a number of temperatures and velocities and then examining the relationship among these, especially with respect to their time-dependent properties. Finally, studies that investigate different routes to chaos receive a great deal of emphasis.\footnote{For discussions of different "routes" or transitions to chaos, see Kadanoff (1983), Bishop (1990), and Rasband (1990, Chapter Three).}

Because of the measurement problem, experimenters in chaotic dynamics investigate and compare the global behavior of systems with types of systems that are better known and
easier to predict. Rather than making forecasts of a phenomenon’s behavior, they concentrate on creating a typology of behaviors and structures observed during experiments, and then relate these to examples of well-known models by analogy (See Chapter Four).

The next chapter consists of background material on language change and language structure, followed by a discussion of Lakoff’s model of conceptual categories. A brief outline of important historical developments in chaos theory is then sketched in terms of Lakoff’s model.
CHAPTER TWO: A Background on Language

SECTION I. Introduction

In the traditional view of scientists and positivist philosophers, language is assumed to be passive. The claim is that since language only mirrors the world, it changes only when new entities are discovered. Language change, if considered at all in this view, is seen as cumulative. That is, the technical vocabulary grows as terms are coined in response to discoveries of new types of events and entities. But while the traditional view holds that the number of terms increases as progress is made in science, this change is not seen as having a substantial impact on the formulation of concepts and theories in science. Language, in this view, is regarded as if it were a true reflection of an external reality.

In this chapter, however, I argue that language is not passive; it affects scientific theories and categorization schemes. Nevertheless, the extent to which language influences scientific change remains to be investigated. In order to understand those properties and mechanisms of language that shape scientific theories, it is necessary to look at how language works.

First, I discuss Ferdinand de Saussure's structuralist theory of language. Structuralism is a semiotic analysis of language; it is concerned with the relationship of signs to
other signs without any account of how signs are related to objects or events in the world. Second, a brief discussion of Roman Jakobson’s criticisms of Saussure’s structuralist theory is presented, followed by a discussion of Charles Sanders Peirce’s pragmatism. Peirce’s semiotic approach is considered here, since it takes into account not only the relationship of signs to other signs, but also the relationship of signs to objects, and their relationship to the user as well.

An assumption of this thesis is that language is continually changing, and so no attempt is made here to explain the occurrence of semantic changes. Rather, I discuss the way that language changes. This distinction may seem unnecessary, but it is as important as knowing that in medieval physics motion was seen as a phenomenon that needed to be explained, while in Galileo’s physics motion was considered to be a natural state of affairs. According to Galileo, what needed to be explained was solely the nature of motion and not motion itself. Similarly, mechanisms of language change, and not the existence of change is what needs to be explained here.

Not all writers considering the influence of language on science have shared the assumption that language change occurs in science. In Linguistic Aspects of Science, Leonard Bloomfield makes the surprising declaration that:

Historical-comparative linguistics will not here concern us, since the use of language in science presupposes complete stability in the habits of
speech. The linguistic changes which occur within a generation or two are relatively minute; such as they are, they disappear entirely under the agreements, explicit and other, which underlie the scientist’s use of language (Bloomfield, 1969:221).

Contrary to Bloomfield’s view of a stable language of science, I argue that the language of science changes, and that this is a normal process. I do not grant the language of science any special properties that distinguish it from everyday language. Furthermore, I argue that language change is not simply reducible to an increase of new terms as science progresses. The changes are more complex and are inextricably intertwined with theory changes. Rates of change vary throughout the language used by a particular field and also across different scientific disciplines. Words are shifted or extended in meaning, new terms are coined, and other terms fall out of use. But most important, the structure of language changes.

A second assumption of this thesis, then, is that language is a system of interacting parts, and that the meanings of words and expressions derive from relations among these parts. In other words, the meaning of a word depends on its place within the structure of the language as a whole. Formal definitions of words often fail to be helpful because they treat words in isolation. The meaning of a word does not simply follow from a set of necessary and sufficient conditions. Rather, it depends on its relationship with other words in a particular context.
The sudden appearance in the nineteen seventies of paradoxical expressions or oxymorons, such as "deterministic chaos," "orderly chaos," and "structured chaos," strongly suggests that the language of science can change dramatically even within one generation, and that the change is structural in nature rather than cumulative.

As Thomas Kuhn observed in The Structure of Scientific Revolutions, theory change is closely related to language change (Kuhn, 1970:126-129, 146, 198-204). I elaborate on Kuhn's suggestions, claiming that during a period of theory change, a complex process of semantic change occurs: one finds, at the same time, new distinctions being made among some terms, along with new relationships of similarity being established among other terms. This process results in bifurcations of word-pairs leading up to major theory changes, and seemingly odd convergences of other pairs as a newly emerging community pulls concepts together in a pattern representing new disciplinary boundaries.

SECTION II. The Structure of Language

The patterns of accepted word combinations form whatever "structure" language may have. Structuralists influenced by the phonological studies of Ferdinand de Saussure and Roman Jakobson believe that the structure of language results from the human tendency to place concepts in binary opposition. A given word or sign does not gain meaning from its dictionary
definition, but rather gains meaning from its opposition to other associated terms (Saussure, 1959:120-121).

Jonathan Culler gives an example of how a word gains meaning from its relations to other words: "... bed is defined by its relations to other words: those which contrast with it, in that they could replace it in various contexts (table, chair, floor, ground, etc.), and those with which it can combine in a sequence (the, a, soft, is, low, occupied, etc.) The former relationship of contrast with other words is called a paradigmatic relation. Contrasting words can potentially substitute for one another in the same slot in a sentence. The latter relationship of combinability with other words is called a syntagmatic relation (Culler, 1975).

Words are syntagmatically compatible with one another to varying degrees. At one extreme, certain words are completely incompatible, as were the words "deterministic" and "chaos" before the nineteen seventies. At the other extreme, words may be so strongly associated with one another that they form a relationship of mutual implication (Culler, 1975:13-15; Benveniste, 1971:20, 36). Again, before the nineteen seventies, the combination of words in the expression "random chaos," was not only compatible, but almost redundant. During the nineteen seventies, however, these syntagmatic relationships changed dramatically.

See also Kuhn (1970:128-129).
The view that meaning depends on relationships of combinability and contrast is not necessarily restricted to structuralist theories. The philosopher J. L. Austin argued in his 1961 essay, "The Meaning of a Word," that to fully understand a word, one has to know not only cases when the word applies, but also cases when it does not. Austin did not believe that it was possible to say what the meaning of a word was without looking at sentences in which the word occurred. Furthermore, he added that one must also look at sentences in which one cannot use a given word. The meaning of the word 'racy,' for instance, is understood, in part, by presenting examples of sentences in which one might correctly use it. But to fully understand the syntax and semantics of 'racy,' it is also necessary to look at examples of sentences and to envision scenarios in which it is inappropriate to use the word 'racy' (Austin, 1961:152).

The linguist Roman Jakobson was influenced by both structuralism and pragmatism. Two main criticisms made by Jakobson need to be brought into our discussion. The first criticism concerns the structuralist emphasis on synchronic studies of language. The second criticism regards the relationship of language to objects in the world, and to its users.

First, although Jakobson was influenced by Ferdinand de Saussure, he criticized him for his exclusively synchronic
studies of language. This approach ignores the historical evolution of words (Jakobson, 1980:17).

A diachronic approach, in contrast, focuses on tracing a term or expression through time (Culler, 1975:12; Bailey, 1973:4). The danger of an exclusively diachronic analysis, however, is that it can be too narrow, restricted to tracking the trajectories of isolated words. To avoid these extremes, the approach taken in this thesis combines an emphasis on both synchronic and diachronic aspects of language; it is a study of historical changes occurring in a whole constellation of interrelated words, similar to Raymond Williams' study of keywords which will be described shortly (see Williams, 1983).

A second criticism of structuralist linguistic theories is that meaning is reduced to a relationship between a signifier (Saussure’s sound image) and a signified (i.e. a concept). Saussure claims that the meaning of a sign does not depend on reference to objects and events. He stated that "the linguistic sign unites, not a thing and a name, but a concept and a sound image" (Saussure, 1959:66). The role of a reality external to language is neglected. Jakobson criticized Saussure’s view of language which considered only the relationship between the signifier and the signified, and in turn, the relationship among different signs.

Because of this deficiency, Jakobson expressed his preference for C. S. Peirce's semiotic view of language over Saussure's semiological view. (Jakobson, 1980:14-15).
Peirce's semiotics as presented in his *Speculative Grammar*, described not only the relationship between sign vehicles (*representamen*) and concepts (*interpretants*), but also considered relationships between those signs and objects in the world. Moreover, Peirce went beyond semantical relationships and investigated the pragmatic dimension, which involves the relationship of a sign with an interpreter as well. Thus, in Peirce's words:

A sign, or *representamen*, is something which stands to somebody for something in some respect or capacity. It addresses somebody, that is, creates in the mind of that person an equivalent sign, or perhaps a more developed sign (Peirce, *Elements of Logic*, 2.228, 2.247).\(^\text{10}\)

In this thesis, I consider a variety of linguistic relationships, ranging from structural to semantic\(^\text{11}\) to pragmatic. The changing structural relationships of words that are in binary opposition play an important role in the formation of conceptual categories. The semantic relationship of signs to denotata takes into account the fact that scientists formulate concepts in response to objects and events in the world. Pragmatic considerations acknowledge that meaning is, in part, dependent on the cognitive and social peculiarities of human beings as language users.

\(^{10}\text{Charles Morris's pragmatics was influenced by Peirce (Morris 1969:107-109, 113; see also Mertz, 1985:2-4).}\)

\(^{11}\text{In using the term "semantic," here, I do not consider meaning in terms of "truth value."}\)
Although it is acknowledged that an exclusively structuralist approach is inadequate, structuralist theories will be used here primarily to explore ways in which concepts, words and signs are identified in contrast to others in a system. Such theories of how meanings are created by contrasts provide an alternative to more traditional ideas that the meaning of a word depends on a set of necessary and sufficient conditions. Furthermore, I explain in Chapter Three how the notion of definition-by-contrast can be used to explicate Lakoff's radial structure model (see Chapter Three).

SECTION III. Conceptual Categories, Language Change, and Communities

A. Concepts Depend on Relationships Among Words

Given our focus on concepts related to the word "chaos," it will not be enough to analyze the meanings and extensions

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12 See Benveniste (1971:37).

13 However, the emphasis on binary opposition is not confined to structuralist theories. The tendency to find meaning by contrast has been explored by many thinkers from diverse intellectual traditions. Peirce, whose work influenced both structuralist schools and ordinary language philosophers, drew on the ideas of Aristotle, Kant, and Hegel to create a new scheme of categorization (Fisch, 1986:263). In his Categories, Aristotle described four different relationships of opposition (Barnes, 1984:18, section 10; But Cf. Parts of Animals (Barnes, 1984:1000).
of that word alone. Austin recognized that the smallest unit of analysis must at least be a sentence. In his essay "The Meaning of a Word," he emphasized that:

what alone has meaning is a sentence. . . . To say that a word or phrase 'has meaning' is to say that there are sentences in which it occurs which 'have meanings': and to know the meaning which the word or phrase has, is to know the meanings of sentences in which it occurs. All a dictionary can do is to suggest aids to the understanding of sentences in which it occurs (Austin, 1961, in Olshewsky, 1969:152).

Following Austin, we examine the word "chaos" in the context of sentences. But it is necessary to go beyond Austin, examining the word in its relationship to the language as a whole.

Philologists and literary scholars have long recognized that understanding a passage of literature from another period of history does not depend on knowing the current definitions of the words. It is not even sufficient to look up the definitions of those words in a dictionary of that time period. Rather, a reader must learn enough about the historical context to be able to understand how the words relate to one another. Or to put it in terms I will be employing here, she must understand the conceptual categories of the culture from which the passage originated.

Individuals who have been absent from a community for several years may find that upon returning they do not quite understand what people are talking about. The difficulty
cannot be resolved by merely looking up a few words; in fact, the individual words seem more or less familiar. What has changed is the way those words are used in relation to one another.

Raymond Williams' study in historical semantics, *Keywords*, was inspired by such an experience. When he returned to Cambridge after his military service in World War II, he discovered that his fellow students used familiar words in new relationships and with different extensions or senses than before the war. Although these changes were in most cases subtle, the overall effect was the uncomfortable feeling that people were speaking a "different language" (Williams, 1983).

The shifting patterns that Williams observed in the structure of the language were a result of intellectual and political changes, and were symptomatic of a restructuring of cultural categories. A major influence on language as a whole, for example, was the new use of the word "culture" in response to a growing interest in anthropology. The anthropological sense was, at first, strictly confined to specialized circles, but then expanded into general conversational English. The anthropological sense of "culture," meaning a "way of life," caused a weakening of the more traditional senses of "socially superior behavior," and

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14See Kuhn (1970:200-201). Also see Chen (1990) for criticisms of Kuhn's incommensurability thesis.
"activity in the arts." But Williams further claimed that, not only did the new sense of the word "culture" affect other senses of the same word, the new extension also influenced changes in a wide variety of words, such as "society," "art," "class," "industry," and "democracy." The result of this semantic shift is described by Williams:

I began to see this experience as a problem of vocabulary in two senses: the available and developing meanings of known words, which needed to be set down; and the explicit but as often implicit connections which people were making, in what seemed to me, again and again, particular formations of meaning -- ways not only of discussing but at another level of seeing many of our central experiences (Williams, 1983: introduction).

One way to study a word, then, is to look at its syntagmatic and paradigmatic relationships to words that are associated with it. As Williams pointed out, it is more revealing to look at connections among words, than to look at words in isolation.

In linguistics, sets of frequently concurring, or associated words are called collocations. One can investigate collocations in general, or one can focus on particular sets of related words, such as collocations of synonyms, collocations of antonyms, etc. (Wardhaugh, 1977:161-162).

Collocations of synonyms for the word "chaos" have changed dramatically in the twentieth century. Before the

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\(^{15}\)See also Pitt (1981:145).
nineteen seventies, the word chaos was collocated with such synonymous words and expressions as "randomness," "noise," and "fluctuations due to stochastic errors." But while the above terms are still used in connection with the term "chaos," in today's scientific circles they are no longer considered synonyms. Because the technical usage of the word "chaos" has changed, these terms are now considered to be collocations of contrasting words and expressions, rather than collocations of synonyms. Also during the nineteen seventies, the word "chaos" was increasingly collocated with adjectives such as "orderly," "deterministic," and "structured." Again, before the nineteen seventies, if these terms were collocated with the term "chaos," they were meant as contrasting expressions. Now, however, they are used more frequently in connection with the word "chaos," and they are increasingly viewed as terms characterizing chaos, rather than as words describing phenomena that are sharply distinguished from chaos.

B. Language Structure and Communities

Conceptual change depends on shifts in associations and contrasts among words. These linguistic relationships, in turn, are partly a function of changes in the structure of a community. Kuhn stresses that investigations as to the nature of scientific changes should start with the study of scientific communities:
To discover and analyze...[scientific changes], one must first unravel the changing community structure of the sciences over time. A paradigm governs, in the first instance, not a subject matter but rather a group of practitioners. Any study of paradigm-directed or paradigm-shattering research must begin by locating the responsible group or groups (Kuhn, 1970:179-180).

In addition to analyzing collocations of words, another way, then, to study a word is to determine the registers in which it occurs. Registers are sets of words and expressions that an individual or a particular community uses for a certain purpose (Wardhaugh, 1977:162). People use different jargons, or argots depending on their occupation, status, and the social activity in which they are engaged at a given moment. The same person may tap different registers depending on the social context. A scientist uses words from a technical register in the lab, but would draw on an entirely different register if she were hanging out in a pool hall after work.

C. A Community of "Chaos Theorists"

One of the reasons that current discourse about chaos theory contains so many paradoxical expressions is due to the mixture of registers from traditionally distinct branches of physics. For instance, early scientific investigations contributing to today's concept of "chaos" were conducted separately in classical dynamics and thermodynamics, and many non-central extensions of concepts in these fields were made
in isolation from one another (Prigogine, 1984:12-14). But in
the nineteen seventies, a new register developed out of the
mixture of a number of previously isolated registers due to
increased communication among members of different
communities. The eventual merging of the two registers
resulted from the creation of new social networks.

For example, when Giulio Casati and Joseph Ford realized
that scientists in isolated fields were studying phenomena
that were somehow related, but were described in the
incommensurable registers belonging to isolated areas, they
organized a conference. The conference took place in Como,
Italy in 1977. According to Casati and Ford:

The fact that completely deterministic, nonlinear
systems can yield wildly chaotic solution behavior
has, over the past two decades, been independently
discovered and re-discovered by numerous scientists
working in a host of distinct scientific
disciplines. Separated from each other by thicket
of specialized jargon and by specialized journals
catering to mutually exclusive audiences, these
workers had remained largely unaware of the
communality of their work. In an effort to break
down this provincialism, the undersigned organized
and held during the summer of 1977 a conference on
stochastic behavior in classical and quantum
Hamiltonian systems which, to our knowledge,
brought together for the first time astronomers,
biochemists, economists, physicists, and
mathematicians working in this common area" (Casati
and Ford, eds. Preface to Stochastic Behavior in
Classical and Quantum Hamiltonian Systems: Volta
Memorial Conference, Como, 1977).

The individual words in the new "chaos theory" register
are more or less familiar to those in other communities, but
due to the shifted relationships among words, an outsider might have the disturbing impression that chaos theorists were somehow speaking a "different language."\textsuperscript{16}

Collocations of synonyms, antonyms, adjectives, and other words used in conjunction with the term "chaos" reveal important differences between the new "chaos theory register" and the old registers from which it was formed. Word combinations such as "deterministic chaos," and "orderly chaos," occur as standard expressions in the new register, but are oxymoronic in either of the old registers corresponding to traditional classical dynamics or to thermodynamics.

Those who advocate the reality construction view believe that language affects thought to the point that what can be expressed varies considerably from one language to the next (Grace, 1987:10). To some extent, this is even true from one register to the next, as is shown in the above "chaos" example. Concepts such as "deterministic randomness," and "orderly chaos," are meaningless nonsense outside of the chaos theory register.

Since registers are sets of terms used by a particular community, they are valuable tools for studying the interaction among scientists, and the impact of this

\textsuperscript{16}See Kuhn (1970:202); See also Fuller on incommensurability, elusiveness of consensus, and conceptual confusion (1988:xiii, 247-248); Also see Chen's criticisms of Kuhn's incommensurability thesis (Chen, 1990).
interaction on theory change. Registers are a useful tool for identifying social groups and disciplinary boundaries.

An investigation into the origins of the oxymorons occurring in the chaos theory register shows that the structure of the language is to some extent a manifestation of the structure of a particular community, as well as an attempted representation of the structure of nature. ¹⁷

The structure of the chaos community is, for example, composed of scientists and mathematicians who had previously been working at the fringes of a variety of disciplines. This is reflected in the paradoxical expressions belonging to the new register. While scientists were admittedly responding to observations, the language used to describe these observations was, in the earliest stages, developed out of different theoretical frameworks: that of classical dynamics, and that of thermodynamics. Each time a term was selected or modified to describe some observed object or event, it was done in consideration of patterns of usage already existing in the relevant community.

¹⁷See Benveniste on Meillet (1971:12).
SECTION IV. Language, Objects, and Communities

A. Conceptual Frameworks

Since users of a language respond to actual events and objects in the world, their language is, of course, shaped in response to these phenomena. Scientists select terms that they believe will best describe their observations. But if they are to communicate with other scientists, they must take into consideration existing conventions and language patterns as well. Since no term has meaning in isolation, scientists must always consider the use of any given term in relation to the accepted uses of terms that are traditionally associated with it. An extension or shift in the meaning of a term, then, occurs within certain limits of the current conceptual framework, although that framework is reshaped (perhaps, at times, only slightly) in response to the new usage.¹⁸

The use of a term, then, is influenced by at least two factors: by its reference to objects in the world, and by the structure of language used by a community. The fact that the language used to describe an object or an event is shaped by a community does not imply that language is an autonomous force creating ideas independently of the natural world. In

fact, communities form in response to objects and events in the natural world.

For instance, various chaotic phenomena stimulated the curiosity of scientists from diverse fields and helped to bring these people together. Observations of such phenomena motivated the initiation of correspondences, the organization of conferences, the founding of societies, and the publication of new journals. Nevertheless, once such a social network is in place, further observations of the given phenomenon are greatly facilitated. The language of a community affects the preconditions for the observation of a phenomenon, acting as a conceptual framework in which scientists carry out observations of objects and events.

B. The Objectivist View of Language

We see that it is inaccurate to say that "language passively mirrors nature." However, those that advocate an objectivist or mapping view, see language as a mirror. The world is seen as carved up into "natural kinds," that is, made up of discrete entities, groups of which are naturally related to one another on the basis of shared essential properties. Further, it is assumed that language is a system of symbols in which the symbols get their meaning through assignment, by convention, to things in the world. Symbolic representations of entities, and groupings of symbols that constitute categories are not seen as in conflict with the structure of
the world. Because of an assumed fit between the mind and the world, a representation of the world can be imprinted on the mind without any significant distortion or shaping by the mind. Thus, language functions as a representation, or map of reality since there is a one-to-one correspondence of conceptual categories and their symbols to entities, or groups of entities, in the world. The entities or members are grouped according to shared properties and relations which meet certain necessary and sufficient conditions (Lakoff, 1987:162, 166).

In the objectivist view, language is seen as almost totally uncommitted -- a blank slate. Thus any language is a "universal encoder," and there are no limits imposed by a particular language on what can be said. Since all languages are mappings of a common world, in this view, the range of what can be talked about does not vary from language to language; all languages are intertranslatable (Grace, 1987:7-8).

C. The Reality Construction View of Language

At the other extreme, in opposition to the objectivist view, is the reality-construction view of language and cognition. In this view, language does not passively mirror an objective external reality, but rather "constructs" a reality. That is, each new perception is shaped, at least to some extent, by concepts already existing in the language.
Those who accept the linguistic construction of reality position do not make a distinction between thinking and putting a thought into words. Since all perceptions are mediated by language, the "reality" that is accessible to human beings is inextricable from the unique influences of their culture, and the language learned as part of the socialization process of that culture. (Grace, 1987:10-11, 118-19).

Benjamin Lee Whorf held a strong version of the linguistic construction of reality view. He believed that language affects thought processes to the extent that people who speak different languages experience different realities or are led to different world views. In his essay, "Science and Linguistics," Whorf argued against the view that language is a passive medium through which people exchange reports about the world. Rather, it is an active shaper of thought. He defended the view that speakers of different languages have different concepts of the same phenomena: "We are thus introduced to a new principle of relativity, which holds that all observers are not led by the same physical evidence to the same picture of the universe, unless their linguistic backgrounds are similar, or can in some way be calibrated" (Whorf, 1956:214).

When describing the way that world views differ, Whorf emphasized that the role of languages in shaping world views was a result of their different systems of categorization.
For instance, Whorf claimed that all languages divide the world into "foreground" and "background" categories, although not necessarily in the same way. Whorf attributed this to the fact that "our psychic make-up is somehow adjusted to disregard whole realms of phenomena that are so all-pervasive as to be irrelevant to our daily lives and needs." He gave an example of a fictitious race of people only able to see blue. The people of this culture would have no term for the word "blue." To them our world "blue" would have no meaning, and would be untranslatable (Whorf, 1956:209-211).

Whorf's observation about foreground and background distinctions in language is relevant to the history of chaos theory. The vocabulary of physics is primarily descriptive of linear phenomena. Depending on one's view of the role of language, this observation leads to different conclusions. On the one hand, those who advocate an extreme objectivist or mapping view of language are led to believe that since the great majority of the terms describing the natural world are suggestive of linear models, then the world must be primarily linear. In this case, the prevalence of terms for linear characteristics is used as evidence for a world that is overwhelmingly linear. According to this view, nonlinear physical systems must then be exceptions since the frequency of terminology describing nonlinear properties is so low.

In direct contrast, those who follow Whorf might interpret the very absence of terms for nonlinear phenomena
precisely as evidence for the all-pervasiveness of nonlinear phenomena in the world, just as in the "blue" example. The presence of an overwhelming number of words and expressions in terms of linear phenomena would only indicate the nature of the cultural experience of a particular community of speakers, and would not be evidence of how the natural world is in actuality.

I have purposely depicted these views in their extremes to bring out the distinction between them. There are many views that acknowledge that conceptual schemes probably involve some combination of world-driven categories and culturally constructed categories, and it is not necessary to adopt either an extreme. The following view is one such alternative.

D. Lakoff's Radial Model of Conceptual Categories

In his book, Women, Fire, and Dangerous Things, George Lakoff adopts a variation of the reality construction view that takes into account the influence of the natural world. He explores categorization schema called idealized cognitive models (ICMs) that involve an interplay between responses to the world and shaping by cognitive and cultural factors (Lakoff, 1987:68).

The ICM schema is based on the premise that the biological make-up of human beings limits the perception of some entities more than others, resulting in asymmetries of
conceptual categories. As a result, then, of the biological characteristics of the human mind, some categories fit the world better than others. Those categories that include objects that are easily manipulated at the human level, or those that are more accessible to gestalt perception, forming simple whole images, are called basic-level categories. Basic-level categories portray the mid-level aspects of the external environment that humans perceive most easily. (Lakoff, 1987:51, 46, 74, 270).

Despite Lakoff’s concession that basic-level categories are more likely to have a closer fit with the world, he stresses that these categories do not merely mirror the world in the way that categories are believed to do in the objectivist view. Although common sense tells us that basic-level categories represent what is real, that feeling of common sense is, in fact, a result of our cognitive limitations and the way that we interact with and process sensory information about the world. Even though basic-level categories are thought to provide the closest fit with the world, they are still shaped by human perception, cognition, and culture, and do not represent an objective or God’s eye view of the world (Lakoff, 1987:50-51, 300).

According to Lakoff, then, most of our knowledge is organized around basic-level concepts. Basic-level categories are cognitive reference points, or prototypes (Lakoff, 1987:41, 45-46). Given a set of related objects constituting
a category, it has been shown through empirical studies in
cognitive psychology that subjects will pick out some members
of the set as **better examples** of the category than others.
For instance, given a list of items that might be grouped
under clothing, such as "shirt," "skirt," "sweater," and
"apron," subjects find "shirt" to be a better example of
clothing than "apron."¹⁹ These "better examples" are called
prototypes.

In the ICM schema, **basic-level categories** can be
correlated with **superordinate** and **subordinate categories**. A
characteristic of basic-level categories, but not of
superordinate or subordinate categories, is that basic level
categories have relatively sharp boundaries. This means that
the members within a particular basic-level category have many
properties in common with each other, but they share very few
properties in common with members of other basic-level
categories; there is maximum perceived similarity among
members of the same basic-level category, but minimum
perceived similarity across different basic-level categories.
Thus, different basic-level categories contrast sharply with
one another, whereas superordinate or subordinate categories
are less distinct (Lakoff, 1987:52-53).

One model of categorization that Lakoff describes is what
is called a **radial structure**. A radial structure has two

¹⁹See Rosch and Mervis (1975).
major parts. The first part of a radial structure is the central cluster, which is a subcategory that is composed of several individual cognitive models. The cluster as a whole is more intuitively understandable, or basic, than any of the individual models that make it up. "Best examples" of a category are understood in terms of the central cluster. In contrast, "poorer examples" are understood in opposition to the central cluster. Thus, the second part of a radial structure is composed of deviations from the central subcategory. These are called noncentral extensions of the cluster (Lakoff, 1987:74-76, 83-91, 204).

The concept of a radial structure is best understood by looking at an example. Lakoff analyzes the concept of "mother" using the radial structure model. In contrast to the objectivist requirement that a category be composed of members which share a specific set of necessary and sufficient conditions, the central subcategory is composed of a relatively flexible set of models. See figure 6. For example, there are several models in the central cluster that characterize the prototypical, or best example of "mother:"

the birth model: the person who gives birth to the child.
the nurturance model: the woman who nurtures and raises the child.
the marital model: the wife of the father of the child.
the genealogical model: the nearest female ancestor of the child.
Figure 6. A Radial Model of Conceptual Categories. The large box contains a central cluster of models that are frequently used to characterize "best examples" of the concept "mother." The circles outside the box denote non-central extensions from the central cluster. Adapted from Lakoff 1987, p. 103.
To be a "best example" of a mother it is not necessary to possess all the characteristics that make up the cluster. In fact, what is considered a best example varies with the social context in which the concept "mother" is brought up.

By contrast, noncentral extensions belonging to a radial structure do not contribute to the concept of a "best example" of a category. These extensions are seen as deviations from the central model, rather than as particular instances of it, and they are defined in contrast to stereotypes and expectations based on the central model. Examples of noncentral extensions of "mother" are: "stepmother," "surrogate mother," and "unwed mother." (Lakoff, 1987:81, 83, 91).

SECTION V. A Linguistic Reconstruction of Conceptual Change in Chaos Theory Based on Lakoff’s Radial Category Model

In this section, I argue that conceptual change in chaos theory can be explained in terms of a modified version of Lakoff’s radial structure model. A survey of early work in chaos theory indicates that there are three important periods in the development of the concept of "chaos."

During the earliest stages (prior to the early nineteen seventies), there was, of course, no single coherent concept of "chaos." Rather, those concepts that now relate to the current idea of chaos existed as non-central extensions of other, more traditional, areas of investigation, such as
classical dynamics and thermodynamics (see Gleick, 1987:181-182, see also Prigogine, 1984:11-12). Non-central extensions of traditional scientific concepts often include categories for anomalous or "recalcitrant" phenomena. For instance, what we now distinguish as chaotic phenomena were in earlier periods lumped with other troublesome phenomena such as "noise" and "stochastic errors."{20}

But by the early seventies, the emphasis was on characterizing chaos as an exciting novelty, rather than merely as a troublesome phenomena to be avoided. As work in this second period developed, continuity with classical dynamics was increasingly stressed rather than discontinuity. The deterministic aspects of chaos were emphasized, while at the same time chaos was characterized in contrast to other phenomena that exhibited fluctuating behavior. Also in this second period, various mathematical models and important physics experiments were increasingly associated with one another and repeatedly brought up in discussions about chaos. Thus, a loose cluster of exemplars was formed. This cluster formed the basic-level category of the concept "chaos."

However, the existence of a cluster characterizing "best examples of chaos," invited not only comparisons, but also contrasts. Thus, in the third period, during the eighties, the focus switched to non-central extensions of the central

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{20}See Lakoff's observation that there is often an "everything else" category (1987:11, 96, 103, 110).
cluster "chaos." The result was that the language used to describe chaotic phenomena underwent refinement as scientists began to look for subtle differences among these phenomena. Phenomena that had been previously lumped together as simply "chaotic," were now differentiated by increasingly specialized terms created to emphasize distinctions among the various non-central extensions of the basic level concept of "chaos." These extensions are often motivated by a desire to link work at the research front with areas of more traditional research.

The exemplars forming the central cluster originate from a surprisingly wide variety of fields, from topology to classical dynamics. In Chapter Three I discuss how a central cluster is formed from a structuralist perspective, suggesting that its identity results from contrasts with other concepts. In Chapter Four I discuss Pickering's interest model as a possible explanation of non-central extensions from the central cluster.
CHAPTER THREE: Creating a Basic Concept of Chaos: The Historical Development of a Central Cluster

SECTION I. Introduction

In this chapter, I describe how a central cluster of a radial model is created. Recall that in Chapter Two I claimed that the discipline called "chaos theory" emerged from isolated non-central extensions of classical mechanics and thermodynamics. As a result of the restructuring of terms and concepts, a central cluster of models characterizing the concept "chaos" was formed. The restructuring of conceptual categories was achieved by means of a change in the way that various terms collocated with the word "chaos" were placed in opposition.

The recognition that binary oppositions have an important role in concept formation is not new. In the article, "A Guess at the Riddle," Charles Sanders Peirce described scientific progress in terms of an early stage in which the theoretical language is dominated by binary oppositions. Meanings of important terms and concepts are created by placing terms in relationships of opposing pairs. Peirce claims that:

> every science has its qualitative stage; now its qualitative stage is when dual distinctions -- whether a given subject has a predicate or not -- suffice; the quantitative stage comes when no longer content with such rough distinctions, we require to insert a possible halfway between every
two possible conditions of the subject in regard to its possession of the quality indicated by the predicate (Peirce, 1890:185:1.359).

While I do not agree that disciplines are necessarily divided into "qualitative" and "quantitative" stages, Peirce's comments about the "qualitative stage" of scientific growth describes the early history of chaos theory rather well.

Although chaos research relies heavily on mathematical derivations and numerical experiments, a significant portion of the accompanying analysis of such research is verbal. 21 While many terms are defined formally or mathematically, the overall structure of these arguments is less explicit. Discussion focuses on dismantling old dichotomies, while suggesting their replacement by surprising new contrasts. Thus, although individual terms are often defined formally, whole concepts, in contrast, are characterized in the structuralist manner by placing terms in binary opposition to other related terms. The meaning, then, of a term describing a concept is often created indirectly, by pointing out the terms that contrast with it.

21See Maddox (1989) "Is chaos Becoming Conversational?"
SECTION II. The "Definition" of a Concept by Binary Opposition

In the early stages leading up to the creation of a central cluster characterizing chaos, scientists found the concept of "chaos" hard to pin down. The notion that simple deterministic equations could produce complex or random results was highly counter-intuitive. In addition, measurement problems due to STIC\textsuperscript{22} placed severe constraints on the ability to explore causal relationships and made it difficult to link the chaos equations with real world phenomena.\textsuperscript{21}

As a result, then, of difficulties stemming from counter-intuitive mathematical concepts and from STIC, it was often easier to say what chaos was not, than to say, exactly, what it was. Thus, the emergence of the concept currently known as 'chaos' took place indirectly. Chaos was characterized by pointing out contrasts with other entities in order to distinguish it from seemingly related phenomena.\textsuperscript{24}

The concept of chaos grew out of a number of isolated problem areas scattered in different scientific specialties in the general areas of classical mechanics and thermodynamics.

\textsuperscript{22}Sensitivity To Initial Conditions.

\textsuperscript{23}See Pitt and Tavel's 1977 article, "Revolutions in Science and Refinements in the Analysis of Causation," for a discussion of similar problems in field theory.

\textsuperscript{24}See Wittgenstein's discussion of defining the word "red" by pointing to things that are not red (1958:14).
When working in these problem areas, scientists often studied such undesirable things as "noise," stochastic fluctuations, unsolvable problems, and ill-behaved functions. These phenomena were often considered to be on the borderline of traditional domains of scientific investigation.

To a great extent it can be said that chaos was defined in contrast to words used to describe this unruly collection of phenomena. Before the nineteen seventies, there was no single concept of chaos. One must look for examples of chaos under many different descriptions. Any one of the terms in the above paragraph could, at one time, have referred to what we now call chaos, even though these terms are generally used today in contradistinction to the term "chaos." ²⁵

When Benoit Mandelbrot began studying phenomena such as "noise" and "errors," he described his investigation as looking through the "trashcans of science" (Gleick, 1985:114).

²⁵Often such peripheral problem areas are what Lakoff would describe as "everything else" categories. An "everything else" category is a category with no internal structure, i.e. a hodge-podge of left-overs that have nothing in common other than that they do not fit into other categories. (Lakoff, 1987:96). An example of an everything else category in science might be a collection of such undesirable phenomena lumped together in a category called "noise." A non-central extension of a category, however, is not completely unrelated to other members. It bears a resemblance to some more centrally located category nearer to the central cluster (Lakoff, 1987:20). A non-central extension, then, exists in some kind of relationship to a central cluster, as opposed to a member of an "everything else" category.
Physicist David Ruelle also tells a story reminiscent of Mandelbrot's experience:

I asked in 1971 a chemist, specialist of these periodic reactions, if he thought that one would find chemical reactions with chaotic time dependence. He answered that if an experimentalist obtained a chaotic record in the study of a chemical reaction, he would throw away the record, saying that the experiment was unsuccessful (Ruelle, 1980:136).\(^{26}\)

Van der Pol's reaction to an unexpected electrical effect also relates to Mandelbrot's claim that many records of chaotic behavior ended up in the "trashcans of science." In the nineteen twenties, the electrical engineer Balthasar van der Pol used the term "irregular noise" to refer to fluctuations that we now call chaotic.\(^{27}\) Because noise was traditionally an undesirable phenomenon that did not fit within any particular area of scientific investigation, van der Pol disregarded the existence of the irregular fluctuations as a mere "subsidiary phenomenon." Instead, he turned his attention to regularities in the signal, which he called "the main effect," ignoring the "noisy" data. Thomas Gleick explains van der Pol's perception of what was important

\(^{26}\)Downey observes that: "'discoveries' of order in nature are hailed as achievements, while discoveries of disorder amount to calls for further research" (Downey, 1988:31).

\(^{27}\)Van der Pol wrote that "often an irregular noise is heard in the telephone receivers before the frequency jumps to the next lower value. However, this is a subsidiary phenomenon, the main effect being the regular frequency demultiplication" (van der Pol, 1927:364).
and what was not as a direct result of language, describing van der Pol as "one of many scientists who got a glimpse of chaos but had no language to understand it" (van der Pol, 1927:364; Gleick, 1987:49; Taubes, 1984:31-32).

The terms "noise" and "subsidiary phenomenon" are examples of theory-laden language. Underlying theoretical assumptions organize conceptual categories, influencing the structure of a particular register. A community's use of this register influences the expectations of scientists who belong to it. In van der Pol's case, the opposition of the category of "the main effect" to the category of "subsidiary phenomenon" influenced van der Pol's research direction, turning him away from a potential discovery of chaotic properties.

Although the term "noise" does not denote the same class of phenomena that it did in van der Pol's time, it is still considered to describe a class of annoying or subsidiary phenomena. Even Robert May's work on population models, which resulted in the reclassification of the term "noise," did not change this. Before May's work, the term "noise" had traditionally been applied to what were assumed to be stochastic influences or, alternatively, to random experimental errors. Depending on the system to be studied, stochastic influences might be environmental factors affecting a population, vibrations due to traffic affecting the measurement of an oscillating system, or Brownian motion.
Neither stochastic influences, nor random experimental errors result from the dynamics of the equations; they are factors external to the mathematics.

May, however, shifted the relationship between the terms "noise" and "chaos" when he pointed out that for some values of the growth rate parameter, the iterated equations modeling population dynamics produced fluctuating values. Because he was only working with an abstract mathematical model, the fluctuations were not due to external factors, such as environmental noise or experimental errors. Rather, the behavior was an essential part of the mathematics of the equations.

It seemed that the fluctuating behavior produced by the mathematics could not be distinguished from that due to external sources. Because May found this ambiguity so disconcerting, he subsequently concentrated on finding ways to distinguish external noise from the internal dynamics of the nonlinear equations. May's journal articles began a tradition of placing the term "noise" in opposition to the term "chaos," in contrast to the earlier tradition in which these terms had been very closely associated and often regarded as synonymous (May, 1974, 1976).

SECTION III. The Role of Formal Definitions

Earlier I argued that the meanings of words cannot be understood solely in terms of formal definitions specifying
necessary and sufficient conditions. More or less following structuralist approach to definition, I have suggested that words and concepts are, to a great extent, characterized by contrasting them to other related terms and concepts.\textsuperscript{28} However, the emphasis, here, on the structuralist notion of definition-by-contrast does not imply that concepts are formed independently of objects and events in the world. Neither does it mean that formal (traditional) definitions play no role in chaos theory. It would be difficult to defend such a claim, especially since many discoveries in chaos theory originate from branches of mathematics in which definitions are greatly valued. Definitions do play an important role in concept formation, but that role is specialized.

The concept of chaos, for instance, cannot be rigidly encompassed within a single definition. Rather, multiple clusters of loosely linked definitions and exemplars constitute the central cluster characterizing chaos. The cluster as a whole, however, is "defined" only by distinctions made with classes of phenomena that are seen as contrasts. Thus, although the cluster contains definitions within it, the

\textsuperscript{28}It may be confusing to the reader that I sometimes use the terms "word" and "concept" interchangeably. My belief is that words are elliptical or synecdochic references to entire concepts. See Lakoff on metonymy (1987, 77-80, 84-85). Nelson Goodman argues that "in a sense, not the word itself but the class it selects is what becomes entrenched, and so to speak of the entrenchment of a predicate is to speak elliptically of the entrenchment of the extension of that predicate" (Goodman, 1955:96).
cluster itself is not defined by a set of necessary and sufficient conditions. The central cluster characterizes a prototypical concept of chaos which gains much of its identity by its contrasting relationship to other categories of phenomena. This prototypical conceptual category is maximally distinct from other basic-level categories, and can be said to be "defined" in the sense that it is placed in contrast to others within an entire structure of conceptual categories.

Although the central cluster is not itself formally definable, it contains many formal definitions. One role of formal definitions is to establish and stabilize a new usage of a term, especially one that is counter-intuitive. An example of this related to chaos theory concerns the use of the term "dimension" when speaking of figures in fractal geometry, i.e. lines and surfaces with a rough or crinkled self-similar structure. The familiar shapes of traditional Euclidian geometry, such as points, lines, triangles, and spheres, etc., are described as having one, two, or three dimensions. But fractal geometry is a non-central extension of Euclidian geometry. While traditional geometry acknowledges only whole number dimensions, fractal geometry includes non-integer dimensions. For those trained to think of dimensions as being integer, the notion of fractional (fractal) dimensions is very counter-intuitive.

A way to think about fractals is to ask how well a winding curve fills a surface, or how well a jagged surface
fills a volume. A line with many folds within folds, for example, fills more of a surface than one that is straighter or smoother. A smoother line has a dimension closer to one, while a line with more nested folds has a dimension closer to two since it fills more of the surface. Similarly, the more peaks and valleys a surface has, the closer its dimension is to three (Peterson, 1988:115). To illustrate this, think of a flat piece of paper. Its dimension is more or less two. But if you crumple it up into a tight wad, it has a dimension closer to three. Its tight nested folds begin to take up a volume as would a solid sphere carved out of wood.

The usage of the word "dimension" in fractal geometry is not merely a generalization of that of Euclidian geometry. The newer usage does not simply denote a broader class of objects than the traditional one. One could perhaps argue that the new usage relegates those shapes with whole number dimensions to the status of being only a special class of objects to which the term "dimension" might apply. But the older system of categorization by whole numbers is not just a special case of the newer fractal geometry system of classification. In the old system, jagged lines would have been classified as one dimensional and rough surfaces would have been classified as two dimensional. Thus, the old system has the capacity to denote about the same number of objects as the new one.
The change that has taken place in the word "dimension," indicates a conceptual recategorization, and not merely a generalization that includes Euclidean theoretical constructs as a special case. The existence of new syntagmatic and paradigmatic relationships is evidence for a structural change in the arrangement of conceptual categories. For instance, in the register of those working in fractal geometry, such terms and expressions as "fractional," or "equals 1.73" may now combine meaningfully with the word "dimension," whereas in the old register they could not. At the same time, in the traditional register, one may say that "depth is the third dimension," or "time is the fourth dimension," but there is no similar pattern in the new register; one does not speak of the "2.89 th dimension." These patterns of combinability and substitutability reveal a restructuring of linguistic categories.

Even within the study of fractal geometry, the term "dimension" does not have a single definition. Rather, the concept "dimension" is associated with a number of slightly differing definitions existing in a relationship of family resemblance.\textsuperscript{29} "Dimension" is a complicated concept, and can be interpreted in several different ways.\textsuperscript{30} S. Rasband's book, Chaotic Dynamics of Nonlinear Systems, describes four

\textsuperscript{29}See Wittgenstein's Philosophical Investigations (1958).

\textsuperscript{30}For further discussion of different definitions of the term "dimension" see Farmer, Ott, and Yorke (1983).
specialized variations of the meaning of "dimension" (although he notes that under certain circumstances there might be more variations): the Capacity dimension, the Information dimension, the Correlation dimension, and the Lyapunov dimension. I discuss only two variations, (and those rather briefly): the Capacity dimension and the Information dimension. While both expressions refer to the degree to which a curve or surface fills up space, the information dimension also takes into account the probability that the curve or surface will occupy that space. This is useful, for instance, when representing a system in phase space. The dimension of an attractor characterizing a given dynamical system may be a function of the probable frequency that a trajectory visits a given region, or a function of the probable density of trajectories passing through that region.\textsuperscript{31} Thus, one role of formal definitions is to adapt a word or expression to a specific context depending on human purposes.

Formal definitions may also be used to initiate and stabilize an unconventional usage, or to establish a term's assignment to a new category. However, subsequent extensions of that term and contrasts with new sets of terms cannot be

\textsuperscript{31}For a more detailed discussion of the various definitions of dimension see Rasband (1990). See also Hurd (1988); Mindlin (1990):2350; Farmer, Ott, and Yorke (1983); Grasberger & Proccacia (1983). For a general philosophical discussion of probability space and phase space, see van Fraassen (1980:196-197).
predicted entirely by the formal definition. These depend on a community's contextually based interpretations of the newly defined term, as well as the reinterpretation of related terms.\textsuperscript{32}

While definitions may act to stabilize a particular usage, that usage may, nevertheless, trigger extensive changes in other related terms. We saw, for instance, that Yorke's unconventional use of the word "chaos" caused changes in the structure of the register pertaining to the physics community, and even eventually affected the registers of other communities. As concepts of nonlinear phenomena changed in response to the new definition, the terms describing these concepts began to shift in relation to one another. Thus, a definition or a new usage can act as a perturbation on the language of a community.\textsuperscript{33}

We saw that changes in the uses of such words as "chaos," "randomness," and "noise" resulted in confusion as to how, in turn, traditionally contrasting words such as "deterministic," and "orderly" should be used. These terms were previously used in opposition to those whose meaning had shifted, but once the original terms had shifted, there was no guarantee

\textsuperscript{32}See Lakoff on motivation vs. prediction (1987:65).

\textsuperscript{33}The relationship between theory change and language change might be described in terms of a virtuous circle. A new usage results in theory change, which, in turn, motivates new usages. Also see Goodman's 1955 discussion of virtuous circles.
that traditional relationships of opposition would still be meaningful. Perturbed by an unconventional usage, the network of traditional syntagmatic and paradigmatic relationships became unstable. It was no longer clear as to when a particular combination of words was nonsensical or paradoxical, and when it was meaningful.

For instance, uncertainty grew as to what the term "deterministic" meant when, in 1963, Lorenz used it in conjunction with the term "nonperiodic" in his article "Deterministic Nonperiodic Flow." Although the article contains mathematical derivations, the nonlinear differential equations are primarily analyzed qualitatively in terms of the behavior of trajectories in phase space. Much of the article is verbal and the key concepts are defined by a series of contrasts.

Lorenz lays out a categorization scheme for different types of trajectories that are possible in phase space. The trajectories are categorized in terms of three binary oppositions: (1) whether a trajectory has transient properties or not; (2) whether a trajectory is stable under small perturbations or not; and (3) whether a trajectory is periodic or not (Lorenz, 1963:132). The focus on binary oppositions in Lorenz' paper recalls Peirce's description of the so-called "qualitative stage" of a scientific discipline, which is characterized by an emphasis on "dual distinctions." According to Peirce, in the early history of a scientific
discipline, a subject is characterized according to whether it has a predicate or whether it does not (Peirce, 1890:185:1.359).³⁴

Lorenz classified the mathematical phenomenon of dynamical systems that exhibit "irregular" or "seemingly haphazard" variations according to the above binary properties of trajectories (selected from the three dual distinctions). Here we only look at oppositions two and three. The second binary opposition considers whether or not the trajectories are unstable. By "instability" Lorenz meant that close-by trajectories would diverge as time increased; in other words, the system was STIC.

In the third opposition, the trajectories of irregular flow were characterized by contrasting them with quasi-periodic trajectories (The class of quasi-periodic trajectories includes periodic trajectories). The distinguishing feature of quasi-periodic trajectories is that for an arbitrarily long period, any two close-by points remain close together. Nonperiodic trajectories, in contrast, demonstrate the divergence associated with STIC. Lorenz noted the consequences of STIC on predictability:

If, then, there is any error whatever in observing the present state -- and in any real system such errors are inevitable -- an acceptable prediction

of an instantaneous state in the distant future may well be impossible (Lorenz, 1963:133).

Because of Lorenz's usage of the word "deterministic" to describe a type of nonperiodic flow which demonstrated STIC, the meaning of "deterministic" shifted in relation to "predictable," since the property of being deterministic no longer guaranteed tolerable long-term predictability.

As a further example, the change in the use of the word "chaotic" resulted in a new relationship between "random" and "deterministic." In 1975, Yorke first used the term "chaotic" in a published article to refer to the nonperiodic output of an iterated equation that was itself clearly deterministic. A tension developed between the sense conveyed by the more common usage of "chaotic" to mean "utterly confused or disordered," and the new specialized sense used in Yorke's description of a nonperiodic, or random sequence of iterates (Li and Yorke, 1975:986).

This confusion is not trivial; discussions of the meanings of the words "deterministic" and "random" continue today, and are often spurred by a slight shift in the meaning of a word closely associated with one of these terms. A recent article by Joseph Ford, "How Random is a Coin Toss?" attempts to expose some of the assumptions behind the meanings of the words "deterministic" and "random," and explores their

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35From the Oxford English Dictionary.
relationship to the word "chaos" in light of current developments in mathematics and physics.

The word "random" is particularly hard to define in terms of necessary and sufficient conditions, since, as Ford points out,

randomness implies a certain lack of order, and because disorder can occur in infinite variety, there is no single calculable test that can rigorously prove a sequence to be random. Individual calculable tests form necessary but not sufficient tests for randomness (Ford, 1983:44). 36

"Randomness" is hard to define because an infinite variety of types of disorder poses not only problems of describability but also of observability. 37

SECTION IV. Binary Opposition and "Material Falsity"

Terms associated with phenomena that are hard to observe may be easier to define in terms of contrasts. Words such as "chaos," and "randomness" are often indirectly characterized by specifying what they are not, rather than by pinpointing exactly what they are. For instance, the term "chaotic" is characterized by contrasting it with other terms such as "noisy," "quasi-periodic," "ergodic," "turbulent," and so on.

36 See also Lebowitz and Penrose (1973) for a discussion of complexities involved with the meaning of the word "random." See also Wicken (1987) for a discussion of the word "entropy."

37 See Goodman's 1955 discussion of the problem of induction.
Similarly, the term "randomness" may be defined negatively as "absence of order," or "absence of an algorithm."

The tendency for concepts to occur in pairs, or in relationships of binary opposition, suggests a mechanism by which ideas about phenomena might be "socially constructed" in some cases. If it is indeed a property of human cognition that every concept automatically implies a concept that is somehow contrasted with it, then it seems that language, in these instances, may appear to assume a life of its own, allowing for a departure from the way the world actually is. After all, just because the mind can produce contrasts with a concept originally resulting from observations, it does not follow that the contrasting concepts actually pertain to anything in nature.

René Descartes grappled with this problem in *Meditations on First Philosophy* regarding the ideas of heat and cold. Descartes discussed "material falsity" in which false ideas are sometimes generated by our tendency to treat the *absence of a certain property* as an existing phenomenon itself. For example, cold is perceived as a phenomenon, although it is not a phenomenon itself, but rather an absence of heat. Descartes noted this tendency of the human mind to reify contrasts, saying that:

*it occurs whenever judgments present a non-thing as if it were a thing. For example, the ideas I have of heat and cold fall so short of being clear and distinct that I cannot learn from them whether cold is only a privation of heat or whether heat is a*
privation of cold; whether both are real qualities or neither is. Because ideas can only be ideas of things, and if it is true that cold is nothing more than the privation of heat, then an idea such as this one, that represents something real and positive to me, will not inappropriately be called false -- and so too for other ideas (Descartes, 1641:73:44).

Thus, we see that the dictum "from nothing, nothing comes" does not necessarily hold when human cognition is involved. This peculiar tendency to reify our abstractions results in the creation of ideas that do not necessarily have denotata. However, it must be emphasized that what is produced are ideas or concepts, and not the phenomena themselves.

Natural processes of language and cognition (such as binary opposition and other mechanisms of semantic change) can extend and add new concepts to a set of concepts derived by observation. The new concepts may or may not correspond to anything actually in the world. The resulting network of concepts placed in structural relationships with one another, and also varying in their reference to actual objects and events, is what I mean by a "conceptual framework."

Nevertheless, a given extension-by-contrast, may, by chance, turn out to correspond to an actual phenomenon in nature (although not necessarily so). Thus, we can see that in those instances when an extension happens to correspond to something, the conceptual framework may function to facilitate further observations. In these cases, concepts created by the structure of language provide a research direction, or
heuristic. But in those cases in which an extension does not correspond to something, the conceptual framework may actually inhibit discoveries by guiding the interests of the scientific community to look in the wrong places for the wrong things.\textsuperscript{38} Nevertheless, there are many cases where conceptual fictions have provided a valuable research direction (for instance "atoms," mathematical constructs such as infinitesimals, phase space, etc.) Thus, correspondence is not a necessary condition for heuristic value.

SECTION V. Summary

Language change has had such a significant impact on the latest developments in science that in journal articles devoted to chaos, a significant portion of space is spent discussing the meanings of such words as "deterministic," "random," "orderly," etc. Such discussions led to new sets of definitions and their variants.

When establishing a new meaning or extension of a particular term, formal definitions can be very helpful; but when explicating a concept, scientists tend to manipulate a network of related terms, shifting collocations of antonyms and synonyms, and restructuring paradigmatic and syntagmatic relationships.

\textsuperscript{38}Consider Descartes' vortices, for instance.
Through a process of binary opposition, chaos came to be characterized by describing it in terms of what it was not. In addition to the primary technical definition of chaos, (STIC), chaos was further defined as "not quasi-periodic," or "not noise," etc. Gradually, the concept of chaos became more and more distinct, and soon the conceptual category characterizing this concept developed the characteristics of a basic-level category.

According to Lakoff, basic level categories have sharper boundaries than do superordinate or subordinate categories. The sharp boundaries occur because members of a basic level category have many properties in common with each other, but few properties in common with members of a different category (Lakoff, 1987:52-53). I have argued that this distinction is achieved by a process of binary opposition.

In this manner the central cluster of the category "chaos" was established, and because of the emphasis on contrasts, that cluster was organized so as to be maximally distinct from clusters corresponding to other categories of phenomena. The set of models, concepts, and definitions constituting the central cluster became recognized in communities of scientists as a more-or-less coherent identity of chaos.
CHAPTER FOUR: The Calibration of Chaos

SECTION I. Introduction

The purpose of this chapter is to show how concepts in an emerging discipline are "calibrated." In chapter three we saw that the identity of a concept is initially defined in contrast to various related concepts, resulting in what corresponds to the central cluster in Lakoff's radial model. In this chapter I show how concepts are also defined by relations of similarity with respect to well known "exemplars" in more mature scientific traditions.

The basic model outlined here is based on Andrew Pickering's interest model of cognitive change in science as described in his article, "Interests and Analogies" (Pickering, 1982). However, I describe Pickering's interest model in terms of the non-central extensions postulated in Lakoff's radial model. Some of the details of my version of Lakoff's radial model are based on the ideas of philosophers such as Ludwig Wittgenstein, J. L. Austin, and Thomas Kuhn, and the philologist Gustaf Stern. These authors describe different conceptual mechanisms which are useful for further explicating the radial model. I argue that scientists employ such devices to establish a research direction (or non-central extension) in such a way that their interests intersect with those of a more established community or tradition.
SECTION II. Exemplars and Interests

According to Pickering, concepts acquire their meaning through exemplars (Pickering, 1982:125). Pickering draws on Kuhn's notion of a paradigm as a "shared example," (an exemplar). An exemplar is a "concrete problem-solution" that is well known in a scientific community. Exemplars are usually encountered by scientists early in their careers, for instance, during undergraduate laboratory experiments or in problems assigned from physics textbooks (Kuhn, 1970:187). A famous exemplar is the usual experiment done with a pendulum to show that for small amplitudes, the period of a pendulum depends only on its length. Exemplars related to pendulums and other oscillating systems are central to many of the diverse fields using chaos theory, such as fluid dynamics, plasma physics, and celestial mechanics.39

Pickering also observes that communities have a stronger interest in the development of some research directions than others, depending on their invested expertise. Because of this bias towards certain research directions, a new exemplar (that is, one at the research front) is constructed so that it "'intersects with the interests' of some particular group or

39 Thomas Kuhn notes that the exemplar of pendulum motion has been used in fluid dynamics for a long time, noting that "Daniel Bernoulli discovered how to make the flow of water from an orifice resemble Huygens' pendulum" (Kuhn, 1970:190; see also Gleick's discussion of the pendulum, 1987:39-40).
groups" (Pickering, 1982:126). Restating Pickering's interest model theory in terms that are used in this chapter, new exemplars must be "calibrated" according to a body of experience in some accepted scientific tradition (which itself contains exemplars) in order to become meaningful. Pickering writes:

What is involved in the articulation of an exemplar? An exemplar constitutes the embodiment of an analogy: some new or 'unsolved' aspect of a scientific field is organized and perceived through a particular exemplary achievement as being the 'same' as some already well-understood aspect of the field (Pickering, 1982:125).

But how is this reorganization achieved? Pickering suggests that language plays a very important role in the recategorization of a problematic scientific area. He gives as an example a group of scientists' strategy to alter their language in order to emphasize the parallel between their own work at the research front, and the well-understood model of an atom:

Now, non-relativistic motion is much more tractable theoretically then [sic] relativistic motion. In particular, the charmonium model depended upon an image of a charmed quark non-relativistically orbiting its antiparticle under the influence of a central potential, in exact analogy with the atomic system of an electron orbiting a positron (the antiparticle of the electron). The latter system is known as positronium, and is one of the textbook applications of quantum mechanics to atomic physics, being almost identical to the hydrogen atom in its formal treatment. The name charmonium was coined to make explicit the parallel between the envisaged structure of the new particles and
the simplest and best understood atomic structure (Pickering, 1982:140).

In previous chapters I argued that language affects theory change, and Pickering's example illustrates this. Nevertheless, the influence of existing language patterns on thought is only one side of the story. We see that in Pickering's "charmionium" example, language users deliberately coined a new term, and used it in conjunction with the existing term "positronium" in such a way as to give the concept of charm credibility. Thus we see that the theories that a scientific community creates are not inexorably determined by language patterns, although such patterns may either constrain or motivate particular scientific changes.

To say that language shapes thought is misleading, then, since this way of putting it anthropomorphizes language, making it seem as if language were some kind of agent. When it is said that language shapes thought, it must be emphasized that what is really meant is that a community of speakers and hearers (or users and interpreters) influences the thoughts of other speakers and hearers (see Benveniste, 1971:22).

A speaker's use of a word or expression can result in intentional or unintentional changes in its meaning. An example of an unintentional change is the change in meaning of the word *beads*. The philologist Gustaf Stern described the change in meaning of *beads* from 'prayers' to 'little balls' in terms of interchanges among speakers and hearers. At one time
beads meant 'prayers,' but since people used to count their prayers by moving the balls of a rosary, the term beads was frequently used in contexts involving the rosary balls, although the original meaning had no connotation of 'little balls.' However, the association was close enough that while the speaker was referring to prayers by the term, hearers would sometimes interpret it in a new way, that is, as referring to the rosary balls (Stern, 1931:173).40

An example of an intentional change might be in the case of the extension of a term to a new set of denotata. Stern gave an example of the extended application of the word "ship" to include steam-ships and air-ships. This type of change can be either intentional or unintentional (Stern, 169-171, 173).

SECTION III. Language as an Instrument

Stern recognized that there is a limit to the extent that individuals can affect language, and conversely, a limit also to the extent that status quo language patterns determine the thoughts of individuals. He describes language in terms of what C. S. Peirce and Charles Morris might call the pragmatic relationship of language to its users, and to what Pickering might call an "interest:"

We must assume that a new name is not accepted by a community or any considerable group within it, if

40See Stern's discussion of permutation and adequation (1931).
it does not in some way meet the demands which are made on speech as an instrument for the promotion of purposes. I assume that, in the same way analogies and possibilities of shortening that offer themselves automatically to the speaker are accepted or rejected according to their suitability for the purposes of speech. . . . We may, then, say of unintentional changes as well as of the intentional ones, that they are the result of the striving of speakers to adapt speech to the purposes for which they make use of it. . . . I conclude then, that most sense-changes are the result of the striving of speakers to adjust speech yet more closely to the functions which it has to perform (Stern, 1931:172-173).

Thus, language is far from an autonomous force governing conceptual change. Even unintentional changes depend on the interests and purposes of language users.

The metaphor of language as an instrument or tool is common among philologists, linguists, and philosophers. This metaphor suggests that language is neither a passive mirror nor an autonomous force, but rather, is actively employed by users depending on their purposes and motives.

Stern referred to language as an "instrument" which speakers can "adjust" depending on their purposes. In "Meaning and Necessity," Rudolph Carnap concluded that "the acceptance or rejection of abstract linguistic forms, just as the acceptance or rejection of any other linguistic forms in any branch of science, will finally be decided by their efficiency as instruments . . ." (Carnap, 1956:221). In his essay "Science and Linguistics," Whorf illustrated the impact of linguistic relativity on thought by saying that observers will be led by physical evidence to the same world-view only
if their linguistic backgrounds can be "calibrated" (Whorf, 1956:214) And Charles Morris made the normative declaration that a scientist should be "held as responsible for the careful use of his linguistic tools as he is held for the careful handling of a balance, microscope, or telescope" (Morris, 1969:71). Despite their diverse backgrounds and viewpoints, these authors at least acknowledge the possibility that language, in some cases, is molded according to human goals and motives. In the following paragraphs I show how speakers deliberately make use of the language -- as if it were an instrument -- to change the structure of conceptual categories.

When Kuhn described the role of language in the maturation of a scientific discipline, he emphasized that the development of a specialized vocabulary occurs alongside the construction and refinement of scientific instruments:

The development of any science . . . calls for the construction of elaborate equipment, the development of an esoteric vocabulary and skills, and a refinement of concepts that increasingly lessens their resemblance to common-sense prototypes (Kuhn, 1970:54).41

41For a detailed account of such refinement, see Pitt and Tavel's case study, "Revolutions in Science and Refinements in the analysis of Causation." They argue that the concept of cause in science underwent successive refinements due to developments in field theory, relativity theory, and Quantum Mechanics. Due to these refinements, physicists' understanding of causation evolved away from a common sense view (Pitt and Tavel, 1977).
I argue here that not only do the processes of linguistic refinement and instrument refinement occur together, but that language itself is an instrument. The concept of "chaos" is "calibrated" by adjusting structural relationships within the language.

During the calibration of a scientific instrument, the identities of signals are determined by comparison and contrast to other signals. On the one hand, signals are calibrated by contrasting them to subsidiary phenomena, such as background noise, while on the other hand, signals are compared to a similar phenomenon that serves as a "surrogate."^42

In a similar fashion, scientists calibrate symbolic categories by contrasting them with certain terms denoting what are viewed as "undesirable" or "uninteresting phenomena," while emphasizing a resemblance to surrogate symbols, or surrogate terms that refer to what are seen as "desirable," "well behaved," or "interesting" phenomena. The distinction between what is seen as a "desirable" phenomenon, and what is rejected as an "undesirable" phenomenon depends, at least in

part, on the interest a particular community has in linking its research to a respected tradition.\textsuperscript{43}

The calibration process depends on how words are used in conjunction with other words. A concept of a particular phenomenon, such as chaos, is understood by a community in terms of the accepted groupings of different words and expressions, such as "noisy," "irregular," "well-behaved," and "deterministic." By deciding which of these words are synonyms, antonyms, metaphors, etc., the community thus calibrates the concept of the phenomenon in question.

In \textit{The Structure of Scientific Revolutions}, Thomas Kuhn argues that following a paradigm shift, the new way in which words are used often entails a radical restructuring of conceptual categories. Kuhn views language as a system, showing that change in the meaning of one word, or the addition of a new term, has reverberations throughout that system. Meaning change in one word also influences the meanings of words that are in binary opposition to it. For instance, Kuhn writes that when the meaning of the word "planet" changed during the so-called Copernican Revolution,

\begin{quote}
the Copernicans who denied its traditional title 'planet' to the sun were not only learning what 'planet' meant or what the sun was. Instead, they
\end{quote}

\textsuperscript{43}Contrast van der Pol's language describing chaotic behavior as a "subsidiary phenomenon" (van der Pol, 1927) to the growing recognition that chaos is a widespread phenomenon that is of importance to almost every scientific specialty (Rasband, 1990; Edelson, 1986; Hofstadter, 1981).
were changing the meaning of 'planet' so that it could continue to make useful distinctions in a world where all celestial bodies, not just the sun, were seen differently from the way they had been seen before (Kuhn, 1970:128-129). "

This example suggests that changes in one word can have a major impact on an entire linguistic system, and that language users make use of this property of the system. A whole network comprised of collocations of antonyms, synonyms, adjectives, etc. may be altered by a slight shift or extension of a meaning. We have seen an example of such extensive change occurring in response to James Yorke's use of the term "chaos" to refer to the nonperiodic output of a deterministic equation.

SECTION IV. Interests Motivate Non-central Extensions from the Central Cluster

While in chapter three I showed how a central cluster of a radial category gains its identity as a maximally distinct basic-level category by its opposition to other concepts, in this section I show how non-central extensions from that central cluster are made depending on a community's interest in selecting a particular research direction.

"See also Kuhn's discussion on pp. 200-202. Of further interest is Xiang Chen's paper, "Local Incommensurability and Communicability." This paper is a thorough, critical discussion of Kuhn's incommensurability thesis (Chen, 1990).
Pickering's interest model provides a possible motive for non-central extensions, and he even hints at a possible linguistic mechanism in his case study of High Energy Particle Physics. However, a look at Lakoff's cluster model gives further insight into possible mechanisms for conceptual change.

The central cluster of a radial model is composed of various exemplars. In this thesis I use a rather broad notion of an exemplar, and include not only highly observable laboratory experiments, but also models, definitions, laws, visual representations, etc. A scientific achievement becomes an exemplar if it is somehow amenable to human perception, cognition, or manipulation. Thus, observability is only one criterion among many. Scientific achievements become accepted as exemplars due to reasons other than observability as well.

It is possible, then, for definitions, simplifications, models, and representations to become exemplary even if they establish only a very weak or even a distorting link with actual phenomena, provided that they are somehow "basic" to human cognition. Recall that Lakoff bases his theory of radial categorization schema on various psychological criteria: susceptibility to gestalt perception, ease of manipulation by natural human motor capabilities, ease of learning, etc. (Lakoff, 1987:36, 46).

Knowledge is organized in a radial pattern, with a cluster of basic level exemplars in the middle, and with
extensions coming out of this center. Thus, basic level categories correspond to objects that are easily investigated by humans, whether or not they correspond to anything in the natural world. In other words, human artifacts and constructs (such as plots of trajectories in phase space) that are highly amenable to the properties of human cognition may be considered just as basic as observed natural events and objects.

In fact, some types of visually oriented artifacts are "highly observable" themselves, although they are not directly related to the natural world since they are representations of theoretical constructs. The repeated use of certain phase portraits (such as the Lorenz attractor) or visual images of topological transformations (such as the horseshoe map or baker's transformation) suggests that they function as cognitive reference points. New discoveries are compared and contrasted to these reference points even though these exemplars are highly abstracted from natural objects and events in the real world. These highly artificial conceptual constructs are prized in the community, however, because they are amenable to the peculiarities of human cognition. 45

45Ian Stewart's article, "Portraits of Chaos," discusses the role that geometrical representations and computers play in the development of chaos theory. He observes that phase space is a conceptual construct that helps scientists to understand the state of a system, say that of a billiard system, in terms their every day experience. Stewart observes that the effectiveness of the phase space construct as a cognitive reference point, or conceptual aid is in part due to the choice of language. He writes: "by using the word
As Bruno Latour pointed out in *Science in Action* (1987), certain human artifacts called inscriptions (graphs, tables, maps, etc.) may have a greater influence on science in some instances than the phenomena themselves. This is because inscriptions are amenable to human manipulation; they have increased "mobility, stability, or combinability." For instance, a map is certainly more mobile than an actual coastline. Also, it is often easier to shuffle inscriptions corresponding to atomic weights and valencies into new patterns (possible arrangements of a periodic table, or possible chemical reactions) than to combine the actual elements themselves. This freedom (although at the price of oversimplification) may encourage new ideas (Latour, 1987:243).

Those scientists studying chaos are well aware that graphs, topological transformations, phase portraits, and computer plots play a central role in the organization of knowledge. Norman J. Zabusky, for instance, argues that computer graphics are a valuable heuristic tool, and he observes that "signatures that show up in graphical displays can serve as nuclei around which a well-prepared investigator can form ideas and concepts. . ." (Zabusky 1984:38).

'...space' it becomes possible to exploit analogies with ordinary space, for example the idea of continuous motion." Nevertheless he reminds the reader that "such a space is 'fictitious', . . ." it is "not the same as the actual physical path followed by the ball on the two dimensional space formed by the snooker table. . ." (Stewart, 1989:42-43).
Inscriptions, then, form part of the central cluster and serve as cognitive reference points.

The central cluster contains exemplars around which knowledge is organized. These exemplars occur in the form of not only inscriptions, but equations, accounts of famous experiments, and definitions. In previous chapters I argued that concepts themselves cannot be defined by a set of necessary and sufficient conditions. Nevertheless, the central cluster of a concept may contain many formal definitions.

However, in addition to a central cluster, a concept also includes non-central extensions. These extensions may be motivated by some set of definitions and exemplars that constitute a prototypical central cluster (either belonging to the same or a different concept), but they are not determined by that set. In other words, non-central extensions are unpredictable (Lakoff, 1987:65, 91). Because of the unpredictability of extensions, then, a concept cannot be captured in a single definition. Rather, a concept is a heterogeneous network of various "models" or "exemplars" that are loosely linked to one another, but do not necessarily share common properties.

For instance, we have seen that the central cluster of the concept of chaos is composed of various "models." The so-called "best example" of the concept of chaos is closely tied to the primary technical meaning of the word "chaos," that is,
"sensitivity to initial conditions." Although STIC serves as a definition, it is only a starting point. Clustered around the concept of STIC are a number of concepts that are loosely linked in a relationship of family resemblance.46

For example, in the literature of chaos theory, STIC is expressed in many different ways: in terms of Lyapunov exponents; in terms of the horseshoe map or the baker's transformation; in terms of various strange attractors in phase space; and even in terms of information theory. The particular variation of STIC that is used depends on the context and the interests of a community in terms of its experience. Different versions of STIC are selected depending on whether one is attempting to measure chaos in a fluid dynamics experiment, or instead, proving a theorem in topology; whether the system one is studying is conservative or dissipative; whether one is working in the tradition of classical dynamics or thermodynamics, etc. This diversity in the available manifestations of STIC allows scientists flexibility in the use of that definition. It is this diversity that allows the central clusters of different radial models to be linked to other models.47


47David Ruelle comments: "To describe the systems which they encounter, physicists, chemists, and biologists use... differential equations. ... One should not underestimate the amount of idealization implied by such a description. Certain parameters are selected as variables... others are ignored, and various simplifications are made" (Ruelle, 1980:132).
Because definitions tend to occur in clusters, and laws and equations occur in groupings of variations related by family resemblances\textsuperscript{48}, at every step, even in a primarily deductive argument a scientist or mathematician has multiple options as to how she will present the next link in the argument. Thus, the chains that form the non-central extensions are \textit{unpredictable}. The extensions are underdetermined by both the empirical data and the rules of deductive reasoning. However, various interests in the community provide \textit{motivations} for extensions from the central cluster, which make some theory changes more likely than others.

Lakoff presents, in detail, a number of mechanisms that explain how extensions are made from a central cluster. One of these, called chaining, is drawn from John Austin's 1961 essay, "The Meaning of a Word." Chaining involves the use of a series of similarity relationships (or analogical relationships) such that, starting with a basic member, A; B is related to A; C is related to B; D is related to C, and so on. A, B, C, and D are locally related to each other, and yet do not share a common set of properties. A and D, for instance, are related only by way of the chain, and bear no similarity to one another by themselves. The chaining model explains how members of a category can be historically related

\textsuperscript{48}See Kuhn (1970:188); See also Wittgenstein (1958).
without the requirement of shared common properties among all members (Lakoff, 1987:18-20, 95-96, 103; Austin, 1961:162-164).

Chaining can occur at the level of models and concepts as well as at the level of individual words. However, it is doubtful whether a distinction between words and concepts ought to be made. If any such distinction is made, I consider words to be elliptical references to concepts, or, in some cases, even references to entire networks of conceptual categories.49

SECTION V. The Calibration of Conceptual Categories by Chaining

An example of chaining used to link an exemplar from the research front to other more traditional exemplars, occurs in the work of Stanford professor of mathematics D. S. Ornstein.

49This relationship of words to concepts is similar to Saussure's semiological theory of signs, in which his term "sound image" (signifier), corresponds roughly to my use of the term "word," and his term "signified" corresponds to my use of the term "concept." My use of the term "word," however, includes not only "sound images," but also written words (Saussure, 1959:66-67). Nevertheless, I prefer the pragmatic theory of signs, or the semiotic view of language, which also considers the relationship of words to denotata and users, as well as to concepts. See also Wittgenstein on what a word signifies (Wittgenstein, 1958:6-7). Also see Goodman's claim that "In a sense, not the word itself but the class it selects is what becomes entrenched, and so to speak of the entrenchment of a predicate is to speak elliptically of the entrenchment of the extension of that predicate" (Goodman, 1955:96).
In his 1989 article, "Ergodic Theory, Randomness, and 'Chaos'," Ornstein attempts to develop a taxonomy of dynamical systems. He endorses the use of a rather simple mathematical model (the baker's transformation) to provide an exemplar in chaos theory, because it is relatively amenable to human cognition, and also because this model intersects with the interests of two established communities that are both doing work related to chaos theory.

Ornstein's extension by chaining goes roughly like this: Chaos is related to randomness. A mathematical mapping technique called the **baker's transformation** can be used as a model of certain random phenomena such as coin tossing. The baker's transformation is deterministic. Furthermore, many systems following Newton's laws can be modeled by the baker's transformation. See figure 7. Thus, Ornstein can reclassify many chaotic systems by choosing a model that relates the two research traditions (probability theory and Newtonian dynamics) by representing statistical properties and trajectories in phase space and looking for "isomorphisms."

According to Ornstein:

> The baker's transformation . . . provides a paradigm for the possibility of deterministic chaos. It can now be shown that this connection is more than an analogy and that at some level of abstraction a large number of systems governed by Newton's laws are the same as the baker's transformation. Going to this level of abstraction helps to organize the possible kinds of random behavior (Ornstein, 1989:182).
Figure 7. The Baker's Transformation. The baker's transformation is used as a model of such random phenomena as coin tossing. The image becomes scrambled due to the stretching and folding operations, resulting in disorder. Nevertheless, the transformation itself is deterministic. It is a deterministic process that produces disorder.
Thus, the baker's transformation (a close relative to the horseshoe map) is used as an exemplar or paradigm at the research front in chaos theory to link chaos with Newtonian mechanics. Note the similarity of Ornstein's words to Pickering's claim that "some new or 'unsolved' aspect of a scientific field is organized and perceived through a particular exemplary achievement as being the 'same' as some already well-understood aspect of the field" (Pickering, 1982:125).

The baker's transformation exemplar was chosen because it is accessible to human perception and cognition, and thus acts as a basic-level concept (in Lakoff's terms). Furthermore, non-central extensions of this exemplar overlap with well established research traditions in both probability theory and Newtonian dynamics. These non-central extensions of the chaos exemplar provide a connection by chaining to two very famous and well established exemplars: the motion of a billiard ball, which is traditionally a model of deterministic systems, and coin tossing, which is a well-known model of random systems. The baker's transformation is shown to be "the same" as carefully selected variants of the above familiar exemplars. These variants, or non-central extensions from prototypical exemplars are the billiard system with convex obstacles, and the tossing of a biased coin. See figure 8. By careful selection and modification of prototypical cases, then, the baker's transformation becomes viable as a new
Figure 8. The Calibration of Conceptual Categories. The baker's transformation is one of many prototypical models that can be used to demonstrate sensitivity to initial conditions (STIC) in chaotic systems. This particular model of STIC intersects with the interests of community members working in Newtonian dynamics and in probability theory. The baker's transformation can be used to model variants (or non-central extensions) of prototypical exemplars in each of these areas of study.
exemplar that intersects with the interests of community members in both Newtonian dynamics and probability theory.

We see that a classification system can be created so that the chaotic behavior looks like an extension of some better understood phenomenon. In chaos theory analogies are often made between exemplars at the research front and traditional exemplars involving billiard balls, tossed coins, roulette wheels, and pendulums.

Pendulum models are used as exemplars in a wide range of fields. In their 1988 article, "Chaos: How Regular Can it Be?" Alexander Chernikov and an associated group of researchers in plasma physics discuss the relationship between the random and deterministic aspects of chaos. Although they are all plasma physicists, very little of the discussion focuses on that field. Instead, their discussion of "deterministic classical chaos" covers quite a broad range of seemingly unrelated areas of investigation: from information theory, to fluid motion, to theories of tessellation. The odd assortment of themes is radially linked, however, to the oscillator, or pendulum exemplar. The authors recognize the central role that this model plays when they write that:

The model of the kicked oscillator turns out to be very versatile. It allows us to achieve a deeper

50 Note the oxymoron. The phrase "deterministic classical chaos" would have been meaningless nonsense less than twenty years ago.
understanding of the nature of chaos by connecting it with certain problems of the symmetry of tilings and other, similar structures (Chernikov, Sagdeev, and Zaslavsky, 1988:34).\textsuperscript{51}

Theory changes are a function of the restructuring of radial categories. Often a non-central extension is abandoned in favor of one that provides a better research direction. The concept of "turbulence" was recategorized in this way. Lev D. Landau, a Russian scientist and co-author of the classic 1959 text on fluid mechanics, proposed what was to remain the standard mathematical interpretation of turbulence until a revolutionary new interpretation was proposed in 1971. Landau's mathematical model predicted that as more energy was fed into a fluid dynamical system, either by pumping or heating, the resulting transition to turbulent flow would be characterized by changes in the velocity culminating in a very large number of independent fluid oscillations during

\textsuperscript{51}See also the 1989 book review by Pomeau, Siggia, and Frisch. They review Nonlinear Physics: From the Pendulum to Turbulence and Chaos (1988), written by Sagdeev, Usikov and Zaslavsky. The reviewers, Pomeau et al., praise the book because of its coverage of the nonlinear pendulum, saying that the portions of the book covering that topic are "of considerable interest" since "many systems are mathematically isomorphic to the nonlinear pendulum or variants thereof. In part 3 the authors take great care to present a wide spectrum of applications: in plasmas, mechanics, optics, atomic physics, solid-state physics and astrophysics" (Pomeau, Siggia, and Frisch, 1989:62). Also of interest, Mitchell J. Feigenbaum comments on an equation widely used to represent a kicked and damped oscillator called the forced Duffing equation. He describes it as a "prototypic equation" (Feigenbaum, 1983:34). While Feigenbaum may not be using the word "prototypic" in exactly the way that Rosch and Mervis would use it, Feigenbaum's description indicates that some equations or models become valued by scientists as exemplars.
turbulent flow. That is, as the energy was increased, the flow would change from having a constant velocity, to one that had a velocity that varied with time in a regular or periodic manner. As the energy was further increased, the velocity would continue to vary periodically, but other periodic motions would intervene. In other words, a velocity having a different value would repeat itself also. According to Landau's mathematical model, this trend of increasing additional periodic motions continues as the energy is increased, resulting in a fluid motion that is characterized by a complicated pattern of distinct frequencies which are not whole number ratios of one another. Such complex motion is called quasi-periodic, and Landau believed that turbulence could be defined as fluid flow that exhibited quasi-periodic motions.\textsuperscript{32} (Gleick, 1987:123-124; Crutchfield, 1986: 48, 54; Ruelle & Takens, 1971:167).

The concept of quasi-periodicity is a natural extension of the concept of periodic motion. It is motion described in terms of many periodic motions combined together to produce a more complex trajectory. Thus, Landau interpreted the complicated and irregular behavior of turbulence as an extension of periodic motion (Ruelle and Takens, 1971:169).

\textsuperscript{32}Although quasiperiodic motion is complex, it is not chaotic. The phase space trajectories of a system that is quasiperiodic do not diverge exponentially, unlike a system that is STIC.
But in 1971, David Ruelle and Floris Takens published their article, "On the Nature of Turbulence," which offered a different interpretation of turbulence. In contrast to Landau, they denied that turbulent flows could be described in terms of either periodic or quasi-periodic functions. Instead, they proposed a new definition of "turbulence" arguing for the reclassification of turbulence based on what they called "ergodic" properties.\textsuperscript{53}

Ruelle and Takens' reclassification of turbulence has a rather complex history involving surprising connections among what are considered very different fields of study. There is no obvious connection, for instance, between the studies of fluid dynamics, oscillators in classical dynamics, and topology. Yet the reinterpretation of turbulence involved a number of historical developments resulting in the chaining of a non-central extension of classical dynamics to topology, and finally to fluid dynamics. The resulting cluster of models became a widely recognized exemplar in the central cluster of models characterizing best examples of chaos.

The story of Ruelle and Takens' reclassification of turbulence begins with a mathematician, Steven Smale, who was studying oscillators. In particular, he focused on nonlinear oscillators, an area that is a non-central extension of

\textsuperscript{53}Ergodic theory describes systems in terms of their long-term statistical or probabilistic behavior (see Ornstein, 1989:183).
classical dynamics. Like Poincaré, Smale investigated the
global behavior of nonlinear systems; he used the approach
known as qualitative analysis of differential equations, and
combined it with the tools of topology.

Smale used the language and mapping techniques of
topology to show that a system could have both the property of
unpredictability, and the property of global stability. To do
this he used a visual representation, the horseshoe
transformation that illustrated both the deterministic and the
random characteristics of chaos.

The horseshoe is produced by a deterministic process of
repeatedly stretching and folding a rectangle within a bounded
region. See figure 9. The random or unpredictable
characteristic of chaos is demonstrated by choosing any two
arbitrarily close points on the original rectangle and showing
that they diverge due to the systematic stretching and folding
transformations. However, despite the divergence of
individual points, the successive horseshoes produced by
stretching and folding display regularities. The persistence
of certain patterns (such as the Cantor set pattern) despite
the stretching and folding transformations is called global
stability. Global stability is demonstrated in physical
systems when the chaotic behavior cannot be removed by
subjecting the system to small perturbations. However, the
inability to predict any particular solution or orbit (due to
Figure 9. The Horseshoe Transformation. The horseshoe transformation is a relative of the baker's transformation. It models the stretching and folding of phase space that is characteristic of systems that are sensitive to initial conditions (STIC). Stretching is the mechanism behind the exponential divergence associated with STIC. Adapted from Rasband 1990, fig. 4.3.
STIC) is what is meant by local instability (Smale, 1967:775; Gleick, 1987:47-52).

Ruelle and Takens used Smale's horseshoe model to challenge Landau's view that turbulence could be described in terms of quasi-periodic motion. The attractor in phase space associated with quasi-periodic motion is a torus (a structure shaped like a doughnut). There are many different orbits on the torus attractor corresponding to distinct frequencies of fluid motion. Quasi-periodic motion is complex, consisting of complicated trajectories winding in different ways about the surface of the torus. But these trajectories do not diverge exponentially, as do points on the horseshoe map. Although quasi-periodic motion is complicated, it does not present the problems associated with STIC (Ruelle and Takens, 1971; Crutchfield, 1986:54).

In contrast to Landau's belief that the motions associated with turbulence could be characterized by a torus attractor, Ruelle and Takens proposed that the motion was of a different kind, having an attractor which they called a "strange attractor" (Ruelle & Takens, 1971:170; Gleick, 1987:133). The strange attractor was described in terms of Smale's horseshoe map. That is, it had a folded structure, but in a bounded region. The repeated foldings of the horseshoe provide a visual analogue of STIC. A cross section
of the horseshoe's folds shows the typical self-similar or scaling pattern associated with the Cantor set. See figure 10.

Since the publication of Ruelle and Takens' 1971 paper linking Smale's abstract topology to fluid dynamics, the horseshoe has become a central model in the cluster of exemplars used to characterize chaos. Because the horseshoe demonstrates STIC visually, exhibiting an easily recognizable Cantor set structure, it has practically become an icon of chaos.

Julio Ottino and a group of associated experimenters in fluid flow have, in fact, produced laboratory experiments on the bounded motion of colored fluids that are analyzed almost exclusively visually (See "the Mixing of Fluids," Ottino, 1989; and "Morphological Structures Produced by Mixing in Chaotic Flows," Ottino, et al., 1988). These experimental instances of real flows are evaluated as examples of chaos depending on whether the colored fluids arrange themselves into a structure similar to Smale's horseshoe. This is especially interesting considering that Smale's horseshoe model was not originally a model of fluid mixing, but rather, a model of van der Pol's electronic oscillator. Ottino and his associates have generalized the meaning of the horseshoe, describing it as: "one of the possible signatures of chaos," and they claim that models such as this can "serve as useful
Figure 10. The Cantor Set Structure of the Horseshoe Map. A line drawn across the horseshoe intersects the folds producing a Cantor set pattern. See also figure 4. This self-similar pattern is characteristic of maps or phase portraits of systems that are chaotic. Adapted from Rasband 1990, figs. 4.1, 4.4, and Gleick 1987, p. 93.
prototypes for various problems in nature and technology . . . " They even suggest that the horseshoe model can be used to analyze geological data pertaining to flows occurring during the formation of the earths's mantle (Ottino, Leong, Rising, and Swanson, 1988:420, 425). Thus, Smale's noncentral extension of the study of oscillators in classical dynamics has become an exemplar in the central cluster of models that characterize the concept of chaos. This has occurred indirectly, through the work of Ruelle and Takens (Smale, 1967; Ruelle and Takens, 1971; Gleick, 1987:51-52; Taubes, 1984:31-32; Ottino, 1989).

SECTION VI. Summary

In this thesis, I have argued that developments in chaos theory can be explained in terms of Lakoff's radial category model. To show how language change affects theory changes I have drawn on material from linguistics, philology, philosophy, and sociology in order to explicate features of the Lakoff model, and I have attempted to explain, in detail, how theory changes are shaped by mechanisms of language change. Lakoff's model is an alternative to the objectivist model in which categories are said to be organized in direct correspondence to natural kinds. Instead, knowledge is said to be organized around human abilities to perceive and manipulate the environment.
A modified version of the Lakoff model serves to explain events in the development of chaos theory rather well. According to this "linguistic reconstruction," historical developments in chaos theory can be explained in terms of: (1) an early period in which models, visual representations, equations, and theoretical principles currently associated with today's concept of chaos, were developed at the fringes (as non-central extensions) of a number of other disciplines; (2) the formation of a central cluster from those scattered non-central extensions of other disciplines; and (3) the development, in turn, of non-central extensions from the newly formed central cluster.

In Chapter Three I discussed the second period during which the concept of chaos gained an identity as a coherent and distinct conceptual category. The formation of the central cluster was explained using a structuralist notion of definition. That is, it was described as a process during which scientists characterized the concept of chaos by contrasting it with other concepts.

In this fourth and final chapter, I discussed the third period, explaining the development of non-central extensions in terms of Pickering's interest model, and in terms of a calibration metaphor. Non-central extensions are "calibrated" or aligned with areas of research that are more securely established.
However, despite the fact that this method of "linguistic reconstruction" is a useful tool for analyzing changes in chaos theory, it must be emphasized that it is a simplification. The history of chaos theory, needless to say, is quite complex.

As mentioned before, STIC (sensitivity to initial conditions) affects measurements. The severity of measurement problems in chaos research has made it somewhat easier analyze the organization of knowledge in terms of prototypes based on human cognitive limitations. Nevertheless, the type of analysis I give here is not necessarily limited to chaotic systems, or to systems that specifically demonstrate STIC. Observation is never unproblematic in any science. Those working in quantum mechanics, evolutionary biology, and astronomy all encounter barriers of one sort or another which pose limitations on observation.\(^4\)

The conceptual categories associated with a given theoretical discourse provide a way of "seeing" by suggesting relationships among various models and exemplars. A categorization scheme, in turn, results in certain patterns of word usage in the language. But coming full circle, new usages can also influence further categorizations and theory

\(^4\)Examples of such barriers to observation include problems related to: the Heisenberg principle of uncertainty in Quantum mechanics; the very limited opportunities for conducting experiments in astronomy; and the difficulties that gaps in the fossil record present to those studying evolutionary biology.
changes. This virtuous circle\textsuperscript{55} can be viewed as a feedback loop, or a process of successive refinement analogous to the calibration of a scientific instrument.

However, in the analogy of the development of scientific theories to the calibration of an instrument, it is important to keep in mind what corresponds to the signals that are being brought into alignment. One should not assume that the language of science is necessarily being brought closer to the actual world, but rather that realms of new experience are being brought into alignment with realms of more established experience. These established experiences occur in the form of exemplars.

Granted, a particular experiment may gain status as an exemplar precisely because it is an instance of a highly observable natural event.\textsuperscript{56} In these instances, terms and expressions describing the experiment may be more securely anchored to nature because it is an easily observable event. In other instances, however, an example becomes an exemplar because of its accessibility to human manipulation, as in the case of the horseshoe map.

\textsuperscript{55}See also Goodman's discussion of entrenchment and virtuous circles (Goodman, 1955).

\textsuperscript{56}The pendulum exemplar is an instance of this kind (although it is debatable as to how "natural" the pendulum experiment is, since, in the classic textbook version, the swing is restricted to a small amplitude occurring in a single plane).
The purpose of the case study in chaos was to elaborate on the nature of this interaction between real world observations, cognitive, and cultural shaping. Lakoff’s radial model provides a limited role for access to reality, while leaving room for cognitive and cultural influences.
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