DOCUMENT RESUME

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| ED 421 340 | | SE 061 533 |

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| AUTHOR | Kim, J. B. |
| TITLE | Analysis of Discovery of Chaos: Social and Cognitive Aspects. |
| PUB DATE | 1998-04-00 |
| NOTE | 25p.; Paper presented at the Annual Meeting of the American Educational Research Association (San Diego, CA, April 13-17, 1998). |
| PUB TYPE | Reports - Evaluative (142) -- Speeches/Meeting Papers (150) |
| EDRS PRICE | MF01/PC01 Plus Postage. |
| DESCRIPTORS | Cognitive Processes; *Computer Simulation; Computers; *Discovery Processes; Higher Education; Knowledge Representation; Physics; *Science and Society; *Scientific Concepts; *Scientific Principles; Scientists; Technology |
| IDENTIFIERS | *Chaos; *Chaos Theory |

ABSTRACT

The purpose of this study was to examine Edward Lorenz's psychological processes and other environmental aspects in the discovery of chaos at that time. The general concept of chaos is discussed based on relations with previous scientific theories such as Newtonian physics and quantum mechanics. The constraints of discovery in terms of available technology at the time of discovery are explained. The following general arguments are made in this paper: (1) the idea of chaos is discovered utilizing the computer and it is hard to investigate without computer technology; (2) Lorenz's accumulated beliefs (knowledge) create a perceptual problem space which is a path toward the discovery of chaos; (3) knowledge can be a tool to guide discovery; (4) the approval of the discovery is a generalized and abstract process; and (5) visual representations give a general picture of the effects of chaos simulation. (Contains 36 references.) (DDR)

# Analysis of Discovery of Chaos: Social and Cognitive Aspects

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Paper presented at the annual meeting of the American Educational Research Association, San Diego, CA: April, 1998



**Running Head : Discovery of Chaos**

## Analysis of Discovery of Chaos: Social and Cognitive Aspects

### Introduction

In the 18th century, the French mathematician Laplace believed that every process and every change could be understood, predicted, and anticipated. The idea of a determined universe is not a recent development in the philosophy of science, but has continued to be the center of attention for many years. Over the last three centuries we have discovered the physical laws that govern matter in all normal situations. The most powerful use of scientific knowledge has been to uncover the causal relations among a set of phenomena and eventually predict one from the other using this knowledge. For example, Issac Newton tried to explain how the stars appeared to move across the sky with his simple laws of motion and theory of gravitation. Therefore, it was assumed that it was necessary to gather and process a sufficient amount of information in order to predict future events.

However, this standpoint has been challenged by the discovery of chaos. Simple deterministic systems with only a few elements can generate random behavior. The randomness is fundamental; gathering more information does not make it go away (Crutchfield, Farmer, Packard, & Shaw, 1986). Randomness generated in this way has come to be called chaos. There are many scientific phenomena which one can not easily predict and show random behaviors such as weather forecasting, predicting stock market trends, and the flow of a mountain stream although those phenomena obey deterministic physical laws. In other words, the dream of complete predictability, which is Laplace's belief, has not yet been realized.

The discovery of chaos has created a new paradigm in scientific modeling (Crutchfield, et al., 1986). Chaos theory has been applied to major scientific fields including mathematics, biology, and physics. In mathematics, chaos theory has been studied in the use of fractals and strange attractors by researchers like Mandelbrot and Feigenbaum. It has also been applied to physics and particularly thermodynamics, the study of turbulence leading to the understanding of self-organizing systems states (Ruelle, 1991; Mullin, 1991). In biology, May (1989) suggests chaotic phenomena in the population growth and identification of plants and animals and Monod (1971) argues that uncertainty (unpredictability) plays a important role in genetics. In recent years, there are growing attempts to incorporate this idea of chaos into the fields of psychology and cognitive psychology in particular (Simon, 1996).

The concept of chaos first appeared in the work of French mathematicians Henri Poincare, Pierre Fatou, and Gaston Julia at various times from 1875 to 1925 (Mandelbrot, 1990; Peitgen, Jurgens, Saupe, & Zahlten, 1990). However, nobody realized their significance as visual descriptive tools and their relevance to the physics of the real world. Chaos was re-discovered by Edward Lorenz, a theoretical meteorologist at the Massachusetts Institute of Technology (MIT). The purpose of this study was to examine Edward Lorenz's psychological processes and other environmental aspects in the discovery of chaos at that time. The following are the general arguments which I am going to make in this paper :

<u>General Arguments</u>

1. Computer as a tool for discovery: The idea of chaos is discovered utilizing the computer and it is hard to investigate without computer technology.
2. Top-down selective attention: Lorenz's accumulated beliefs (knowledge) created a

perceptual problem space which is a right path toward the discovery of chaos.

3. Knowledge as a tool to guide a discovery: Although Lorenz discovered chaos by accident, it might not have been possible unless Lorenz had previous knowledge of mathematics and non-linear dynamic systems. In other words, he would have thought that the difference was just noise in the data or problems with the computer.
4. The approval of the discovery is a generalized and abstract process: Lorenz generalized his complicated weather model by testing simplified version of it.
5. Visual representations as auxiliary artifacts: Lorenz intentionally made a graph in order to understand his simulation effect along with numerical representations. In the study of chaos, the common activity among scientists is creating various visual representations because they give a general picture of the effects of simulation.

In this paper, the general concept of chaos will be briefly discussed based on the relations with previous scientific theories such as Newtonian physics and quantum mechanics. Then, the constraints of discovery in terms of available technology at the time of discovery will be described. In addition, Lorenz's psychological processes during the discovery will be discussed. How his background knowledge affected the discovery will also be examined.

## The Concept of Chaos

### Chaos : Historical Context from Henri Poincare to Edward Lorenz

A chaotic system is one in which the final outcome depends very sensitively on the initial conditions (Ruelle, 1991). For example, the motion of a billiard ball is precisely determined by the initial condition. The deterministic model can not do well with regard to long term range prediction. This is because we know the initial condition with a certain imprecision : we cannot distinguish between the "true" initial condition and the many "imaginary" initial conditions that are very close to it.

Issac Newton's theory of gravitation clearly brought cause and effect into the picture. It established entirely new mathematical framework for both describing and explaining the moon's motion. In Newton's model three celestial body problems, the motion of Earth, moon, and sun, are difficult to solve. Newton admitted that he failed to explain the three body problems using his theory of gravitation (Peterson, 1993).

Henri Poincare's theoretical work demonstrated that the solutions of the equations expressing Newton's laws in cases of three or more bodies encompass not only the periodic and precisely predictable, but also the irregular and unpredictable. Poincare proved that the motion of three bodies under the influenced gravity can be extremely complicated. His discovery was the first evidence of what is now called chaos: the ability of simple models, without inbuilt random features, to generate highly irregular behavior. Landau, a Soviet physicist, believed that the complex dynamic system cannot be predictable. However, his theory has been disapproved by Poincare, because he proved that even very simple systems can show very irregular behaviors (Crutchfield, et al., 1986). Although Poincare (1952) had articulated many of the basic ideas underlying the notion that deterministic systems could sometimes display unpredictable behavior, few scientists had bothered to struggle through the technicalities of their predecessor's massive works on celestial mechanics to recover those ideas (Peterson, 1993).

A seeming paradox is that chaos is deterministic, generated by fixed rules that do not themselves involve any elements of chance. In principle, the future is completely determined by the past, but in practice small uncertainties are amplified, so that even though the behavior is predictable in the short term, it is unpredictable in the long term. There is order in the chaos underlying chaotic behavior which are elegant geometric forms that create randomness. Mitchell Feigenbaum found universal number associated with the way systems approach chaos (Gleick, 1987; Lorenz, 1980).

In summary, chaotic systems can be summarized as follows. First, chaotic systems are deterministic. This means that chaotic systems follow deterministic physical laws. Second, chaotic systems are very sensitive to the initial conditions. A very slight change in the starting point can lead to enormously different outcomes. This makes chaotic system fairly unpredictable. Third, chaotic systems appear to be disorderly, even random, but they are not. Beneath the random behavior is a sense of order and pattern; truly random systems are not chaotic.

## The Discovery of Chaos

### One day in 1961 at MIT

The discovery of chaos happened by chance. One day in the winter of 1961, Lorenz took a shortcut when examining one sequence of a simulation of a weather model. Instead of starting the whole run over, he started midway through. To give the machine its initial conditions, he typed the numbers straight from the earlier printout after dropping a three digit number from original data. Much to his surprise, the results he got this way were very different from the results that he had gotten previously by running the calculation all the way through. Lorenz's (1993) immediate assumption was that the computer had a problem, because of the unreliability of computers at that time.

However, he soon realized that the problem was with the data he put in the weather model. Initially, the result was similar to the old output, but the new output diverged radically from the old output after simulation of two months of data within a fifteen month period (see Figure 1).

Insert Figure 1 About Here

## Lorenz's Strange Attractor

Edward Lorenz published a paper after three years discovering a chaotic phenomena in 1961. He published the paper under the title of 'Deterministic Nonperiodic Flow' in the American "Journal of the Atmospheric Sciences" in January 1963. This paper described the work that Lorenz had been doing for the previous three years on a mathematical model of a weather system in his laboratory at the MIT. In the paper, he included his strange attractor which is the final product of his discovery (Lorenz, 1963).

In order to explain his strange attractor, a simple pendulum could be used. All that is needed to determine its motion are two variables : position and velocity. The state is thus a point in a plane, whose coordinates are position and velocity. Newton's laws provide a rule, expressed mathematically as a differential equation, that describes how the state evolves. As the pendulum swings back and forth the state moves along an "orbit" path in the plane. The motion of a simple pendulum will show periodic motion which settles down to a fixed point.

Insert Figure 2 About Here

However, Lorenz's strange attractor produced by his weather model neither settles down to a fixed point nor does it have periodic motion (see Figure 2). Therefore, it is impossible to predict what the future state is going to be (Lorenz, 1963; Lorenz, 1993).

## Socio-Psychological Process in the Discovery of Chaos

There are many socio-psychological aspects which allowed Lorenz to discover chaos. First, there had been growing global interest and effort to build efficient weather forecasting systems and models at the time of discovery (Lorenz, 1993). Second, important technological advances had been achieved in this era. John von Neumann designed a machine which enabled meteorologists including Lorenz to simulate weather models easily (Gleick, 1987). In addition, this computer technology also made it possible to produce other forms of representations such as graphics and diagrams efficiently so that chaos problems could be visually understood (Devaney, 1989; Mandelbrot, 1990; Peitgen, et al., 1990). Third, Lorenz looked at the problems differently than other meteorologists at first. In other words, his problem representation for the atmospheric system was quite different than that of other meteorologists back in 1950's and 1960's. Fourth, he had a fairly comprehensive mathematical knowledge compared to other meteorologists and he could communicate with scholars in other domains using this tool. Finally, Lorenz used visual representations, such as graphs and line, along with numerical representations in order to understand the effects of weather model he was working on. In general there are three major socio-psychological schemes that can be extracted from among these: (1) knowledge as a guiding tool, (2) technological constraints, and (3) visual representations. Therefore, these three issues will be the focus of this section.

**Theory driven Selective Attention**

Cognitive psychologists such as Gibson (1969) and Marr (1982) claim that humans perceive information in a data driven way. That is, features or attributes of information are processed first and then these features are compared to information stored in memory. However, Gestalt psychologists and schema theorists like Minsky and Schank disagree with the idea that information stored in memory is actively engaged in recognition and perceptual process. It might be true that these two aspects work interactively when perceiving information.

Lorenz tried to develop a weather model which does not settle down to a steady state and he believed that aperiodicity and unpredictability are related to each other. An underlying problem representation from his understandings of the atmosphere enabled him to discover new phenomena in the future. No other theorists in the field had this kind of explanatory model. His theoretical background (knowledge structure) guided him to recognize the importance of chaotic phenomena which he created by chance. Basically, His knowledge structure was built upon the strong belief and experiences for deterministic views of physical phenomena (e.g., beliefs about Newtonian physics and experiences in mathematics). A piece of evidence for how his theory selectively affects on attention is related to the selection of which equations he was going to use in his research. Lorenz was working on developing the simplified deterministic model which still has a property of sensitivity on initial difference after discovering chaotic phenomena. Lorenz did not form a weather model by himself and his simplified weather model come from Barry Saltzman who is a meteorologist at the Travel Weather Center. While Saltzman was only interested in variables that settled down, Lorenz was interested in variables that refuse to settle down; in other words, weather models that have the attribute of aperiocidity (Lorenz, 1993). Thus, his conceptual knowledge of atmosphere did affect his choice of the equation to study.

A second piece of evidence is that when Lorenz first noticed the chaotic phenomenon, he was able to pay attention to the underlying structure of chaotic phenomena. His immediate attention to the phenomenon comes again from the fact that he already had a rough concept of relations between aperiocidity and unpredictability, although he did not have empirical evidence. If he does not have general idea of non-linear system when he look at the discrepancies between the original data and regenerated data, then he may interpret discrepancies in his data differently.

**Conceptual change and Knowledge as a tool**

Domain specific knowledge is crucial to many scientific discoveries because those discoveries are less likely to happen if scientists do not have knowledge of the domain (Dunbar, 1995). In addition, many scientific discoveries are based on analogies made across different fields and from collaborative work so knowledge in a domain could be useful in other field as well. Dunbar's (1993) experiment shows that subjects who could use scientific background in a domain do better in the discovery of biological concepts.

Lorenz's domain knowledge played a crucial role in understanding what he found and communicated with others. Probably, he may not have understood the importance of what he found without his extensive background on dynamic systems and mathematics. His paper in 1963 demonstrates this. He was able to do further analysis on the chaotic phenomena utilizing his background knowledge on the field of mathematics. Poincare, who also had a glimpse of chaos theory, had extensive mathematical knowledge of differential equations. Therefore, both Poincare and Lorenz had a strong tool by which to articulate their ideas. Because Lorenz was mathematically competent, his work could be noticed by other scholars later.

Until the time when Lorenz discovered the concept of chaos, he gradually changed his concept of atmosphere. Before discovering the concept, he already had a rough idea about what a dynamic system such as a weather model should be. He was not satisfied with the current weather model at the time of discovery which was made based on a statistical model. He strongly believed that a non-linear weather model better explained real weather situation. He clearly saw the disadvantages of a statistical weather forecasting method which cannot present the idea of non-linearity, even though he was member of statistical weather forecasting community. Thus, because his process of discovery was guided by his preexisting idea, his discovery is not a totally surprising result.

Lorenz did not stop at the point of finding the butterfly effect, in order words sensitive dependence on initial difference. That is, he does not believe that an image he produced was not representing pure randomness because of his previous deterministic view of a dynamic system. Lorenz's earlier career in mathematics and dynamic systems allowed him to view things in a Newtonian fashion. He continuously attempted to explain the possible underlying structure or order of chaotic systems. In this case, the knowledge led him to discover the concept of chaos as well as maintain his beliefs about a deterministic model. In the latter case, his knowledge of mathematics and a dynamic system provide explanatory model for understanding order in chaos.

**Generalization and abstraction as a conceptualization process**

A weather system can be considered an enormous experiment in fluid dynamics, with air being the fluid. There is turbulence, pressure, temperature differences and a whole host of other things to take into account. Therefore, to create a system of equations to model the atmosphere in every small detail would be an enormous task. From this reason, Lorenz decided to base his model on just a dozen equations. Thus, twelve variables (equations) are used when he discovered chaotic system.

Gooding (1992) proposed that scientists often do demonstrative reconstruction to generate evidential arguments from accounts of a particular experiment. Schank (1988) also suggests the importance of generalization process in scientific activities. Lorenz's strange attractor, which is the simpler version of fractal geometry was developed through experiment and abstract thought processes; in other words, a reconstruction process. Lorenz started to look for a simpler system that had sensitive dependence on initial conditions after finding an unusual phenomena. When he discovered the chaotic phenomena, he used twelve equations. In further analyses, he tried to come up with a much simpler version that still had this attribute in order to make a generalization (Lorenz, 1993). He took the equations for convection and stripped them down, making them unrealistically simple and having nothing to do with real weather systems. The system no longer had anything to do with convection, but it did have sensitive dependence on its initial conditions and there were only three equations this time. Lorenz simplified his twelve equations because he wanted to reconstruct his experiment again. Part of reason is that he wanted to formalize his idea in order to write a paper in the future (Lorenz, 1993).

However, the main reason is that he wanted to prove that chaotic nature appears in a simple dynamic system. What he tried to do at that time is that he wanted to generalize his thoughts to a more extreme context because he wanted to prove that even simple deterministic models can have chaotic phenomena. This generalization or abstraction process not only enabled him to make a strong argument, but it was a cognitively effective strategy because he could not mathematically handle twelve variable equations mathematically at once. Finally, Lorenz reduced his model to a three-variable weather model which is a cognitively manipulative form (Palmer, 1991). This is exactly what Henri Poincare exactly did a century ago when he tried to solve a three celestial body problem in order to make generalizations to n-body problem (Peterson, 1993). In the scientific discovery, the abstraction process helps to change conceptual structure (Nersessian, 1992).

Lave (1988) points out that human cognition is situated in social contexts. Similarly, Salmon (1993) suggests that cognition is distributed over different people. Many scientific discoveries do happen in a collaborative environment (Latour & Woolgar, 1986). However, it is not the case that social practice or distributed cognitive aspects are played an extensive part in the discovery of chaos. Although Lorenz did get some motivational encouragement from other meteorologists, he did not know the work of Poincare or Hill (Lorenz, 1993). In addition, most of researchers in meteorology did not believe what Lorenz thought. Many scientific discoveries are the product of collaborative work or scientists getting a new idea or alternative solution from colleagues from his or her scientific community. However, Lorenz did not have this kinds of support.

<u>Technological constraints of discovery of chaos</u>

Computers are the primary tool for studying chaos, and much of our understanding of chaotic systems comes from running computer models that trace these systems through time. A typical research problem would be solved like this: an equation that describe a system is written down and solved on the computer. The starting point of the calculation is then changed slightly and the calculation repeated. If the predictions in the two solutions are wildly different (e.g., producing completely different whether predictions by slight changes in initial data points), the system is chaotic and more detailed investigations are done. There are two aspects that make it a crucial artifact in the field of chaos.

First, the powerful computational ability of the computer is needed in order to study chaos. When John von Neumann invented a modern computer, he optimistically believed that the perfect weather forecasting was possible in the future. The field of meteorology has developed substantially because of the power of the computer. Lorenz (1993) stated that it might not have been easy to discover the concept of chaos without using a computer, although his computer was primitive regarding its computational capability. Computers are crucial tools needed for chaos experimentation, since chaos related calculations are repetitive and laborious work. For example, in order to produce Mandelbrot Set on a single screen, it takes an estimated six million calculations.

Lorenz (1993) described the importance of computer technology in his discovery of chaos as follows:

> It seems reasonable to conclude that, once computers had been around for a while, their contribution to the growing awareness of chaos extended well beyond their application to the hitherto unlovable equations in specific problems pursued by individual scientists. . . . Without computer the needed time for computation alone would have been years instead of months. (p.128-129)

Second, Latour and Woolgar (1986) suggest that there are many "inscriptive devices" in scientific laboratories which are tailored for special purposes in those laboratories. The role of computers in the work of Lorenz is essentially reification of his theory of chaos. What Lorenz did prove is that the computer as a realization of Newtonian deterministic science can demonstrate unpredictable and radical changes in outcomes from small changes in initial values. The computer simulation reified the abstract thinking of chaos. The error which he did not include three decimal points produced radically (disproportionate) changes in output. Using a computer as a tool, he was able to see this dramatic effect because he could simulate long range time periods so that he could see the full effects of chaotic phenomena. If he calculated this by hand, he would not have noticed this phenomena because he only could computed small time period of outcome.

<u>Use of visual representations</u>

Visual representations are crucial to the sciences and engineering (Latour, 1990; Henderson, 1991). This is part of scientific culture so that people can communicate and understand each other. These visual representations are cognitively effective in enhancing memory, representation of material, and saving cognitive load (Shepherd, 1988). In the course of transforming verbal propositions into images, many things are made explicit that were previously implicit and hidden (Simon, 1989). Visual representations help us make additional inferences and understand other forms of representations such as scientific notation and words. Qin and Simon (1990) suggest that visual representations such as diagrams are important in understanding scientific concepts.

There is much evidence which suggest that scientists and inventors have been predisposed to use visualization in their acts of creative imagination and discovery (Rieber, 1994). For example, the German chemist Kekule reported that he used mental imagery in order to understand molecular structure of benzene. Faraday also used this technique to visualize the lines of magnetism (Rieber, 1994). In the earlier part of the 20th century, the French mathematician Julia did understand the beauty of fractal geometry. However, he did not have a tool to represent the idea in his mind (Peitgen, et al., 1990). Mendelbrot (1977, 1990) was able to do this because of the graphical presentation power of the computer which became available in the 1970's. Lorenz also might not have found a chaotic phenomena without computer technology.

As I described earlier, Lorenz tried to develop a simplified weather model which only had three variables because he wanted to have a cognitively manipulative form of a system so that the system could be tangible. In addition, his simplified model enabled him to produce a graphical representations of the modeling effect (Palmer, 1991; Lorenz, 1963, 1993). In other words, a maximum number of three variables can be visually represented in two dimensional space (i.e., paper or computer screen). If a model has two variables, it can be visually represented using a piece of paper which is a two dimensional space. Of course, it is not easy to visually represent a three variable model in a two dimensional space, but it can be efficiently represented on a piece of paper or computer screen. However, if he used the original twelve-variable weather model, then it is realistically impossible to represent his model because the model needs twelve dimensions.

It is uncertain whether he made a three-variable weather model because of the possibility of visual representation. However, it is certain that Lorenz wanted to visually represent the result of simulation using a simplified weather model along with numerical representation. In this respect, his simplified weather model does have a strong advantage. Lorenz's simplified model can, therefore, be represented by a point in a three dimensional 'phase space', and the evolution of the weather with time can be represented by a line, trajectory, on a piece of paper (Lorenz, 1993). He intentionally drew graphs to help understand the system's behavior. Lorenz (1993) stated as follows:

> I wrote an alternative output program that made the computer print one or two symbols each line, their distances from the margin indicating the values of one or two chosen variables, and I would often draw a continuos curve through successive symbols to produce graph. It was interesting to watch the graph extend itself. (p.134)

In his 1963 paper, Lorenz used various visual representations. Therefore, understanding chaotic phenomena is easier using graphical representations in addition to the numerical representations.

It is the visual representations that helped computer technology play a crucial role in the discovery of chaos. One of the most interesting examples is fractal geometry (Mandelbrot, 1977, 1990; Jurgens, Peigen, & Saupe, 1990). The study of nonlinear systems has only been made more accessible with the advent of computers. The patterns of complex, nonlinear systems often only show themselves when the data is converted into visual form. The innate human ability of pattern recognition in combination with computer's forte of working through millions of iterations with complex data structures have allowed many of the mysteries of chaotic systems to be explored and better understood.

The computer revealed the subtle behavior of chaotic systems because it can follow their trajectories over many millions of steps. This approach has exposed the abstract geometrical nature of chaos theory in the form of computer graphics.

## Conclusion

The discovery of chaos theory significantly impacted modern science. Many scientists believe that twentieth century science will be known for only three theories : relativity, quantum mechanics, and chaos. Aspect of chaos show up everywhere around the world, from the currents of the ocean and the flow of blood through fractal blood vessels to the branches of trees and the effects of turbulence.

The importance of computer technology and knowledge based on tool perspective for the discovery of chaos was discussed in this paper. Lorenz gradually developed his problem representation from careful observation of real weather and simulation of a weather model so that this made it possible to discover chaotic system. Thus, his discovery is not a surprising result to some extent and it was expected because he had appropriate knowledge structures (schema) for the discovery (e.g., knowledge of dynamic sciences and mathematical background). In addition to this, computer technology facilitated the discovery. Conclusively, chaos theory has resulted from a synthesis of conceptual ideas and readily accessible computer power.

It is interesting to see that Lorenz's work was not much involved with other scientists' work. While many researchers such as Latour and Woolgar (1986) argue that many scientific discoveries are products of collaborative work and the interdisciplinary collaboration, the discovery of chaos is not much related to this theoretical scheme. Although Lorenz interacted with many other meteorologists around him, it seems that he did not get much help from others in terms of the discovery. He even was not aware of the previous work of Poincare and Hill (Lorenz, 1993). There is also great time gap between his discovery and the popularization of the idea within the scientific community. In fact, his landmark paper, which was published in 1963, was not even discussed until decades later. Part of reason might be the fact that he did not publish the paper in mathematics or physics journals considered as the core scientific fields (Lorenz, 1993; Gleick, 1987). This reflects the fact that there is often great deal of isolation among different scientific communities. This lack of communication among scientific fields may hinder new discoveries and diffusion of discoveries difficult.

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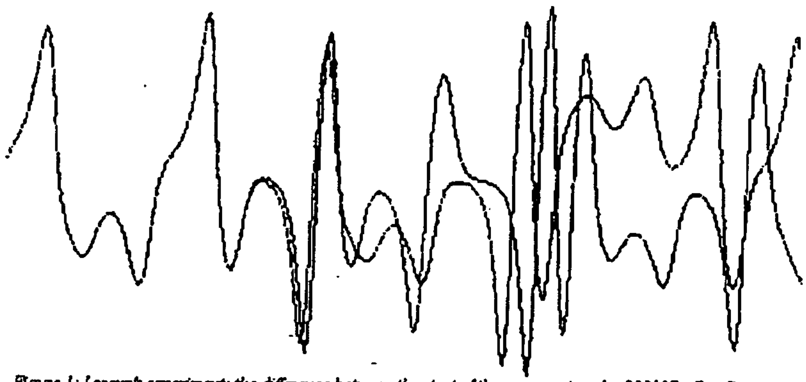

*Figure 1: Lorenz's experiment: the difference between the start of these curves is only .000127. (Ian Stewart, Does God Play Dice? The Mathematics of Chaos, pg. 141)*

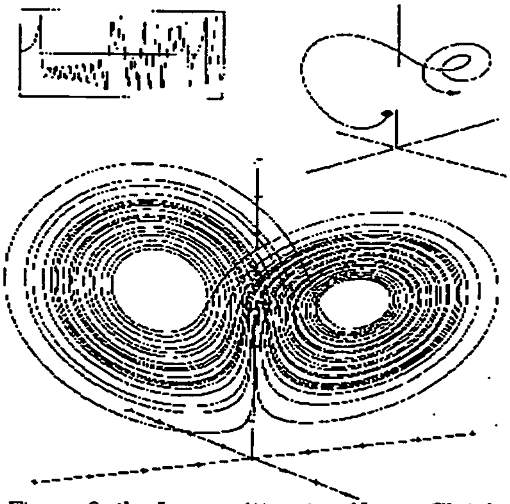

*Figure 2: the Lorenz Attractor (James Gleick, Chaos - Making a New Science, pg.29)*

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