PART V

WHEN IS ORDER DISORDER?

This section relates to the recent developments in chaos theory which pose significant questions for the historic scientific worldview, and it relates to the Christian doctrines of eschatology and the sovereignty of God. How does the indeterminacy of quantum physics relate to chaos? What are the implications of chaos for the idea that history is moving toward a culmination point?

What is the relationship between predictability and chaos? A great value of science is its ability to predict, to relate cause and effect. For example, eclipse dates can be calculated thousands of years into the past or future. There are systems that obey the laws of physics, yet generate random behavior. The roll of dice, the flow of a mountain stream, and the weather are all such phenomena; all have unpredictable aspects. Scientists now realize that simple deterministic systems can generate random behavior. Such behavior is called chaotic.

Is the physical order moving toward a culmination (eschatology)? How is the present reign of Christ (exaltation) over the created order to be understood? How does “chaos” relate to the free will/predestination debate?

Does the presence of chaos make a case for a dynamically involved Creator, such that the world is constantly emerging from chaos (Gen. 1:2)?
CHAPTER THIRTEEN

CHAOS THEORY

In previous chapters we have dealt with the science of the very large (chapter 4—cosmology) and the very small (chapter 10—quantum theory). In this chapter we will deal with the science of everyday objects that cause us headaches. Here we will examine questions such as: Why does the ketchup not flow regularly from the bottle? Why can the dripping of the kitchen faucet be so irregular? Why cannot the weathercaster get the weather forecast correct? Why did the character Malcolm keep talking about chaos in the book and movie, Jurassic Park? The science of chaos deals with these frustrating and seemingly unrelated areas. In this chapter we will see why chaos theory has allowed scientists to discover order in certain apparently random processes. We will also examine the effects of chaos theory on our philosophical view of our world.

The Weather

As we discussed in chapter 10, for years astronomers have used Newton's laws to predict the future positions of planets or comets. Although the atmosphere has more particles than the solar system has planets, the same laws govern the behavior of the particles in the atmosphere. Meteorologists believed all that was needed was enough data to specify today's weather and a computer large enough to calculate the weather forecast for tomorrow. By the 1950s and 1960s, meteorologists were optimistic that they could achieve their goal of long-term weather forecasting. More and more weather stations—to collect temperature, pressure, and wind speed/direction—were being built; and large, powerful computers were becoming available. No one intended to do a calculation involving every particle in the atmosphere. Rather, they would
model the atmosphere by including only those factors that are important in forecasting. This type of modeling is common in science. For example, when an astronomer calculates the path of Halley’s Comet, she does not include every heavenly body in the calculation. She would not include other galaxies. She would only include the planets that cause the greatest effect on the comet’s path.

In 1960 one person attempting to model the weather was the American meteorologist Edward N. Lorenz at the Massachusetts Institute of Technology. Lorenz had created a model of the weather involving twelve equations that related factors such as the temperature, pressure, and wind speed. Every minute his computer printed out a row of numbers that represented a day of weather. A review of the printout, line by line, gave the impression that his model was following earthly weather patterns. Pressure rose and fell; air currents swung north and south. One day he decided to repeat a set of calculations. In order to save time, he decided to start the calculations at the midpoint of the run. He entered the appropriate numbers from his computer printout and began the calculations.

Because the computer in his office was noisy, Lorenz left to get a cup of coffee. When he returned an hour later, he discovered, to his surprise, the results obtained were different from his first run. After just a few “months,” all resemblance with the previous run was gone. How could this be? The results of this recalculation should have been the same since he was using the same program. After examining how his program worked, Lorenz realized that the computer used six-digit numbers (.506127) in its calculations. To save paper the printout was only to three digits (.506). The difference of one part in a thousand had resulted in vastly different behaviors for his system. Lorenz’s finding was amazing since a scientist would usually consider himself lucky to reproduce two measurements with this level of precision. Lorenz had discovered a system that was very sensitive to initial conditions. Today we would say that Lorenz had discovered chaos.

To further analyze the behavior of systems sensitive to initial conditions, Lorenz decided to simplify his system. He developed a three-equation/three-variable system that did not model the weather but did model convection, a part of the atmosphere. Convection is the bulk movement of heat through a fluid. In his 1963 paper1 Lorenz listed the output of his calculations: (0,10,0); (4,12,0); (9,20,0); (16,32,2); (30,66,7); (54,115,24); (93,192,74).
Lorenz obtained hundreds of these triplets. He wished to determine how the variables changed with time; one way to analyze this output is to graph the data which Lorenz did. Lorenz used each set of three numbers to represent a point in a three-dimensional space. The result of this plot would be a series of points. Connecting these points yields a continuous path which is a record of the system's behavior.

Fig. 13.1. Lorenz Attractor.

Lorenz discovered that the resulting pattern looks like an owl's face or the wings of a butterfly (see Fig. 13.1). The path weaves back and forth between the "wings," never repeating itself. The behavior signalled disorder since no path ever recurred. At the same time the behavior signalled order since all the paths were confined in the overall pattern. Since each set of initial conditions will result in a different path within the overall pattern, Lorenz concluded
“that prediction of the sufficiently distant future is impossible by any method, unless the present conditions are known exactly. In view of the inevitable inaccuracy and incompleteness of weather observations, precise very-long-range forecasting would seem to be non-existent.” Thus, Lorenz is saying that because of the complexity of the atmosphere we can never have enough information to perform accurate weather forecasts.

### Chaos

What is this chaos that Lorenz discovered in his weather model? How does it vary from everyday use of the words *chaos* and *random*? Looking up these words in the *Oxford English Dictionary* reveals that the word *chaos* comes from the ancient Greek concept of the original state of the universe as a formless void out of which the *cosmos* or order came. Thus, a chaotic state is one of utter confusion or disorder. The word *randomness* comes from an old French word meaning “to run fast” or “to gallop.” Thus, something is random when it follows a haphazard course or is without aim or direction. Both of these words imply confusion or disorder.

Science also uses the terms *chaos* and *disorder*, along with the term *nonrandom*. In science these terms are distinguished by their degree of predictability. A *nonrandom* process is one that in theory and in practice allows predictability. When one thinks of the triumph of the scientific method, one is thinking of this predictability. Using the law of gravitation, one can predict eclipses thousands of years into the future or past. A *random* process is totally unpredictable. What has happened previously gives no clue as to what will happen next. Raindrops hitting a surface represent a random process because the arrival of one raindrop gives no clue to the arrival time of the next raindrop. A *chaotic* process falls in between these two extremes of total predictability and total unpredictability. Because equations can be written to describe the behavior of chaotic systems, they are in theory predictable. Yet, in practice, they are only temporarily predictable and eventually become unpredictable.

### Attractors

How different is the behavior of Lorenz’s system from other dynamic systems? *Dynamic* systems have constantly changing
conditions in contrast to static systems. To obtain a picture of the behavior of the dynamic system, scientists graph the changing values of the systems variables. The resulting graph is called a phase space, which is a plot of the system over time. The phase space plot provides an idea of what the behavior of the system is like. With time, the graph will settle into a geometric shape called the attractor. The dynamic behavior is "attracted" to this geometric shape.

Fig. 13.2. Fixed-Point Attractor for a Playground Swing.
There are four kinds of attractors: fixed-point attractor, closed-curve attractor, torus attractor, and strange attractor. Figure 13.2 shows the behavior of a playground swing as it moves back and forth. Eventually, the swing comes to rest at a fixed point, its attractor. Start the swing again and it returns to this attractor.

Fig. 13.3. Closed-Curve Attractor for a Pendulum Clock.
Drop a stone and it comes to rest at a fixed point on the earth, which is another example of a fixed-point attractor.

Not all attractors are fixed points. Some are cycles. A pendulum clock replaces its energy lost to friction by a spring or weight. Thus, the pendulum clock continuously repeats its swing. The attractor of the pendulum clock is a closed curve (see Fig. 13.3). The closed-curve attractor for the moon is its orbit around the earth. Systems can have more than one attractor, depending upon the initial conditions for the system. If the pendulum clock has only a small displacement of its pendulum, it will quickly come to rest—a fixed-point attractor. A large displacement sets the clock to ticking—a closed-curve attractor.

Another attractor is the torus (doughnut) which is seen in certain electrical oscillators. Imagine a torus attractor as walking on a large doughnut, going over, under, and around its surface. The paths taken by the fixed-point, closed-curve, and torus attractors are not sensitive to initial conditions.

The path taken in a strange attractor is sensitive to initial conditions. The strange attractor was named by the Belgian mathematical physicist David Ruelle and the Dutch mathematician Floris Takens in 1971. Strange attractors represent the behavior of a chaotic system. Strange attractors are complex, three-dimensional shapes that have detailed structure at all levels of magnification. If you magnify a section of a strange attractor, it never looks simpler; it looks complex on all levels. This behavior is like “a set of wooden Russian dolls, each containing a smaller replica of itself within.” Strange attractors are represented mathematically by fractals. A fractal is a complex geometric shape whose small-scale and large-scale structures resemble each other. Figure 13.4 shows a Koch snowflake, which is a fractal formed in just four steps by adding small triangles to the sides of larger triangles.

To understand why chaotic systems lose their predictability with time, we need to examine the attractor for a chaotic system. The attractor for a chaotic system is much more complicated than a predictable system attractor such as a fixed-point, closed curve, or torus. In a predictable system attractor, the paths that start near one another remain near one another. Or start a pendulum clock with a certain force and the system settles into the closed-curve attractor; change the starting force by a factor of one part in a thousand and the pendulum clock will settle into the “same”
A fractal is a geometric shape whose large-scale and small-scale structures resemble each other. An example of a fractal is the Koch snowflake which can be made by adding small triangles to the sides of larger triangles.

Fig. 13.4. Example of a Fractal.

closed-curve attractor. Thus, the system is not very sensitive to initial conditions, and predictability is maintained.

Different or "strange" behavior is observed for a chaotic system. With a strange attractor, the paths that start near one another quickly diverge. It is as if the attractor space is being stretched; a model of this behavior could be the stretching of a lump of bread dough during kneading. This divergence of the paths is exponential. An attractor is finite and thus the paths cannot diverge forever. Thus, the attractor folds onto itself; again, this can be modeled by the folding of bread dough after it has been stretched. The paths of the attractor are shuffled by the folding. The stretching and folding of the paths makes the system very dependent upon initial conditions. Now one can imagine why a one-part-in-a-thousand change in initial conditions caused the system to follow a different path as Lorenz observed. The stretching and folding continues repeatedly, creating a fractal. Also the stretching and folding of the paths replaces the initial information with new information. Predictability is short-lived. Long-term, all causality is lost.

Just how sensitive are chaotic systems to initial conditions? Before the concept of chaotic systems, it was assumed that all systems are predictable and that the accuracy of the prediction depended on the accuracy of the measurements of the system variables. Chaotic systems changed this view. As an example, for a very simple mathematical model of a chaotic process, measuring the values of the variables to one part in a thousand allows one only to predict the sequence of events for twenty-four steps. Increasing the
accuracy to one part in a million increases the predictability to forty-eight steps, with one part in a billion giving predictability to seventy-two steps. For nonchaotic systems there would be no limit to the number of steps for the predictions. For many variables, it is not practical to obtain an accuracy of one part in a million, let alone one part in a billion. In addition, most “real world” chaotic systems are more complex than this mathematical model, which would require even greater accuracy to maintain these levels of predictability. In all chaotic cases, one quickly comes to the point where predictability breaks down.

**Transition to Chaos**

Many dynamic systems begin as ordered, predictable systems and then change to a chaotic system. We remember a scene from a movie where a character puts a lit cigarette on an ashtray. The camera focuses on the smoke. Initially, the smoke rises in a smooth stream (order). Then, suddenly, the top of the smooth stream becomes wildly erratic and swirls in all directions. The behavior of the smoke has gone from *laminar* (order) to *turbulent* (chaos) flow. Other examples of the transition to turbulence from our everyday life occur when a regularly dripping faucet changes to a randomly dripping faucet, or when ketchup smoothly flowing from a bottle onto our fries suddenly acquires an erratic flow and lands on us as well as the fries.

Turbulence has always been lurking in scientific systems. In many cases it could be ignored, so the systems were studied as ordered. In others, turbulence could not be ignored, so the systems were ignored. Engineers hate turbulence. Turbulent airflow removes the lift from an aircraft’s wing; turbulent oil flow in a pipeline causes drag. Until the advent of chaos theory, few thought that turbulence would ever be understood. A scientific myth says that the quantum physicist Werner Heisenberg said that he had two questions for God: why relativity, and why turbulence? Heisenberg is quoted as saying, “I really think He may have an answer to the first question.”

An important question is how flow can change from smooth to turbulent. Or more generally, how do ordered systems become chaotic? Is there a way to predict when this transition will occur? One clue to understanding this transition came from the American biologist Robert May, who was studying annual variations in insect populations. One might expect that a high growth rate would lead
to a larger population while a low growth rate would lead to a smaller population, with extinction occurring if the growth rate is too small. Using a mathematical model which predicted next year's population based on this year's population, May studied the effect of an increasing growth rate on the population value. At low values for the growth rate, the population would settle down to a single value year after year.

At first increasing the growth rate increased the population to another stable value. Then a surprise happened. As soon as the growth rate passed a value of three in his model, the possible population value branched (bifurcated) into two solutions. The model was still being deterministic (predicting a solution); it was now predicting two solutions. At this new growth rate, the population would be at one value one year followed by the other value the next year; then the population values would repeat. Increasing the growth rate a little more caused the population value choices to jump from two to four; the model was still deterministic. Continuing to increase the growth rate would lead to four bifurcating to eight, eight into sixteen, and so on with the model still being deterministic. At a value of 3.57, chaos began in his model. At this point, it became impossible to predict future population values; all one could say is that the population value would be one among all the values in the strange attractor. Field biologists found that May's model did reflect the behavior of actual animal populations.

Is May's work applicable to other systems that make a transition from predictable to chaotic? An answer came from the American physicist Mitchell Feigenbaum, who studied May's work and proposed that the transition to chaos involves what is called period doubling (the bifurcation that May observed). This is called the period-doubling route to chaos. It was also realized that the period doubling comes faster and faster until the sudden appearance of chaos. Feigenbaum determined a numerical constant (4.669) that governs the doubling process (Feigenbaum number). He also discovered that these results (period doubling and Feigenbaum number) were applicable to a wide variety of chaotic systems. At last science had a way to predict the onset of turbulence.

Applications

As scientists acquired an understanding of chaotic process, they realized some processes that they thought were random were
actually chaotic. In some cases, the chaotic model allowed scientists to explain puzzling observations. In other cases, scientists now had a tool for predicting the beginning of chaos and thereby at last being able to prevent the beginning of chaos. A few examples of the application of chaos theory to problems in astronomy and medicine will be given.

Astronomy

In astronomy, scientists have mostly used chaos theory to explain observations. Certain regions of the asteroid belt between Mars and Jupiter are almost free of asteroids. Scientists assumed that the gravitational field of Jupiter had resulted in these gaps; but until the advent of chaos theory, scientists had no mathematical model for these gaps (called Kirkwood gaps in honor of their discoverer). Calculations, using chaos theory, show that the interactions between the motions of the asteroids and the motion and gravitation field of Jupiter create chaotic regions in the asteroid belt. Most of the asteroids are expelled from these chaotic regions, resulting in the Kirkwood gaps. The expelled asteroids are sent on a path that takes them toward the inner planets. Thus, some of the expelled asteroids cross the orbit of Earth; such asteroids have the potential for colliding with the Earth and causing great damage. Chaos theory gave scientists a framework to explain and tie together these two phenomena.

Most natural satellites (moons) in the solar system have an orbit period equal to its spin period. For example, the moon takes twenty-seven days to orbit the earth and twenty-seven days to rotate on its axis. This results in the same side of the moon always facing the earth. Hyperion is a potato-shaped satellite of Saturn. Hyperion has an erratic spin period and a constantly changing rotational period. Calculations, using chaos theory, indicate that the behavior of Hyperion is chaotic because of its interaction with Saturn and Saturn's large moon, Titan.

Medicine

In medicine, chaos theory has not only given scientists an understanding of why certain phenomena occur but in some cases a regimen for preventing the onset of certain conditions. The body's defense mechanism against disease has been analyzed as a chaotic process. When the body is invaded by a bacterium or virus, the body, apparently, tries defense strategies at random.
feedback loop is used to tell (indicate) when a correct strategy has been selected. Scientists are trying to mimic this process in drug development.

Analysis of historical data for the two childhood diseases, measles and chicken pox, revealed that their epidemics behaved differently. Chicken pox varied periodically, while measles varied chaotically. This means that at a certain number of measles cases, it is "impossible" to predict in which direction the epidemic will proceed. The strange attractor for the measles outbreaks helps epidemiologists see patterns in what had previously been "random and noisy" yearly data.

Several medical conditions, including heart fibrillation and attacks of epilepsy and manic depression, involve a transition from an orderly process to a chaotic process. Fibrillation is also called ventricular fibrillation. The ventricles are the two large pumping chambers of the heart that discharge blood to the lungs or body. The normal ventricular contractions of the heart are periodic, controlled, and coordinated. Fibrillation involves ventricular contractions that are rapid, uncontrolled, and uncoordinated. Under these conditions the ventricles cannot pump blood and death can occur unless the condition is corrected. Normal heartbeat can sometimes be restored by a massive electric shock to the chest using a defibrillator. Chaos theory has helped physicians in two ways. The period-doubling-to-chaos trend allows those monitoring a patient to detect the beginning of the transition to chaos and to intervene before fibrillation starts. Understanding of the strange attractor for fibrillation has allowed for the better design of defibrillators.

The Scientific Method and Chaos

As we saw in chapter 1, one approach to the scientific method is to verify a theory by testing predictions. We compare the flight of a ball predicted by a mathematical equation to the actual flight of the ball. For more complicated systems such as a collection of gas molecules, a scientist would use statistical techniques to examine the properties of the system rather than the properties of the individual gas molecules. The system properties are statistical averages of the properties of the individual molecules. Simple mathematical equations relating the system’s temperature, pressure, and volume can be found. (Reducing the volume increases the temperature and pressure of the system.) No attempt is made to explain the variables for an individual gas molecule.
What about chaotic systems? Very short-term predictions are possible; in billiards, the agreement between the predicted and actual path of a cue ball is lost in a minute or less. Long-term predictions for chaotic systems are impossible. Long-term, the best one can hope for is agreement with the strange attractors. Even with this agreement, chaos is not explaining very much more than statistical techniques. Neither method is giving predictive information about the individual components.

Chaos challenges reductionism. Reductionism says that the whole can be understood by breaking it down and studying its parts; if one can determine the forces and components present, then one knows everything about the whole. This view has been very successful in physics and chemistry. Many scientists are now attempting to extend reductionism to biology; they believe if one can determine all the physical interactions and chemical reactions present in a living system, then one can totally explain that system. Chaos has shown that complex behavior arises from simple, nonlinear interactions of the system’s components. This implies that the whole can be more complex than the sum of its parts.

Usually we emphasize the limitations of chaos, the loss of predictability. However, others have speculated about the positive effects of chaos in nature. It has been proposed that nature, by amplifying small fluctuations, creates novelty. Scientists wonder: Do prey use chaotic flight controls to evade predators? Does a chaotic process introduce genetic variability? Does creativity have an underlying chaotic process?

**Summary**

Chaos is not the same as randomness. Although chaotic systems are deterministic with mathematical equations that relate the behavior of their components, they lose long-term predictability. Chaotic systems have three characteristics: sensitivity to initial conditions, strange attractors, and period-doubling route to chaos. Chaos theory challenges the predictability that undergirds the scientific method; it also challenges reductionism. Although chaos may be seen as a limitation to our understanding of nature, chaos may be the mechanism by which novelty is introduced.