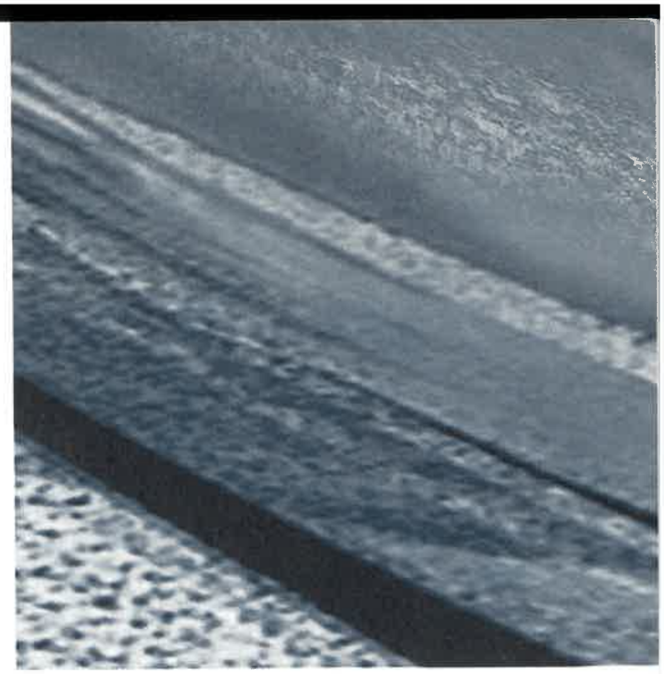
CHAPTER 2

Daisyworld

An Introduction to Systems



Key Questions

- What are systems?
- What are feedback loops?
- What are equilibrium states?
- Does viewing Earth as a system allow for deeper insight into the interrelationships among the physical and biological worlds?
- Can Earth's climate be self-regulating?

Chapter Overview

In this chapter, we develop the fundamentals of systems theory needed for the study of Earth as a system. First, examples from everyday life are used to introduce the important concepts of systems theory. Then we introduce the simplified climate system of the imaginary planet Daisyworld. Daisyworld is subjected to an increase in solar luminosity even more rapid than that which Earth has experienced over its history. Yet the hypothetical planet is able to counter the tendency for warming by increasing the reflectivity of its surface (by allowing for the spread of white daisies). We will see that this seemingly intelligent response arises without foresight or planning but rather as a natural consequence of interactions within the system. Through such feedbacks, natural systems can remain stable despite disturbances. Although the climate system of Daisyworld is oversimplified, we suspect that feedbacks like those it exhibits have played an important role in stabilizing Earth's climate over geological time.

THE SYSTEMS APPROACH

The systems approach has been used in virtually every area of inquiry, including branches of both the natural and social sciences. Human physiology is a good example of where the systems approach is particularly illuminating. The human body is made up of a number of systems that perform the vital functions of life: a respiratory system that takes in oxygen and eliminates carbon dioxide; a cardiovascular system that circulates the blood, carrying oxygen and carbon dioxide around the body; a digestive system that processes food to fuel all body processes; a nervous system that senses changes in the internal and external environments and controls the activities of the other systems; an endocrine system that regulates ongoing processes such as growth and development; and so on. These systems are interrelated, functioning together to maintain the human body in a healthy state.

The Essentials of Systems

Each **system** is an entity composed of diverse but interrelated parts that function as a complex whole. The individual parts of a system are called **components.** A component can be a reservoir of matter (described by its mass or volume), a reservoir of energy (described by temperature, for example), an attribute of the system (such as body temperature or pressure), or a subsystem (such as the cardiovascular system, one of the interlinked subsystems of the human body). The components of the cardiovascular system itself include blood cells, blood vessels, and the heart.

The **state** of a system is the set of important attributes that characterize the system at a particular time. Body temperature, level of nutrition, and blood pressure are among the attributes that determine the state of the human body. The components of a system interact in such a way that a change in the state of the system is "sensed" throughout the system. In many systems, this linkage allows for the control of important attributes. For example, the endocrine system of the human body is capable of maintaining a nearly constant internal temperature despite large changes in the temperature of the surrounding environment. Suppose that your body temperature starts to rise as the air temperature around you rises. Your hypothalamus, a component of the endocrine system, then directs your sweat glands to increase their production of sweat, which helps cool you. If the ambient temperature then drops, your hypothalamus stops sending the signals to your sweat glands.

Couplings

It is clear from these examples from human physiology that the components of the human body "system" do not exist in isolation. They are linked, allowing for the flow of information from one component to the next. These links are called **couplings.** To understand how couplings allow for system regulation, consider an electric blanket. You set the temperature of the blanket (one system component) by adjusting a temperature controller. You adjust this controller to achieve a body temperature that is comfortable.

A *systems diagram* (Figure 2-1) allows us to keep track of the various couplings within a system. In a systems diagram, couplings are conventionally represented by arrows. There are two types of couplings. In the example of an electric blanket, an increase in blanket temperature causes an increase in body temperature; such a link is called a **positive coupling** (Figure 2-1a). In a positive coupling, a change (increase or decrease) in one component is a stimulus that leads to a change of the same direction in the linked component. When one component increases, a positively coupled component responds by increasing. When the first component decreases, the second component responds by decreasing. A positive coupling is represented by a solid arrow with a normal arrowhead, →.

In contrast, an increase in body temperature above the comfort level would lead you to *decrease* the amount of heat by turning down the controller. This coupling, from body temperature to blanket temperature, is a **negative coupling** (Figure 2-1b). In a negative coupling, a change in one component stimulates a change of the opposite direction in the linked component. When one component increases, a negatively coupled component responds by decreasing. And when the first component decreases, the second component increases. A negative coupling is represented by an arrow with a circular arrowhead, —o.

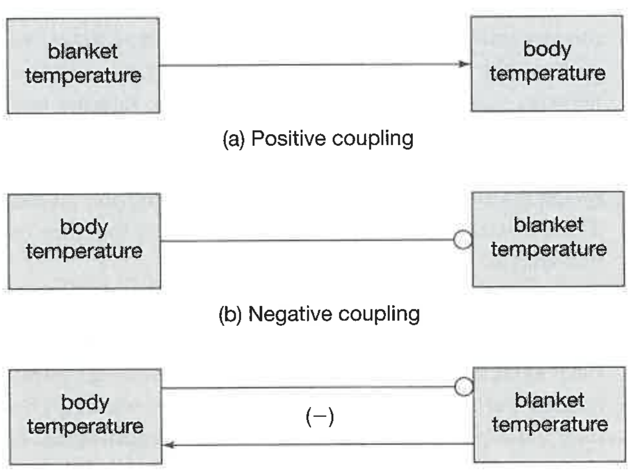


FIGURE 2-1 Systems diagrams; a negative feedback loop. (a) An increase (or decrease) in blanket temperature causes an increase (decrease) in body temperature—a positive coupling. (b) An increase (decrease) in body temperature causes you to decrease (increase) the blanket temperature—a negative coupling. (c) A negative feedback loop is created by the two couplings.

Feedback Loops

The two couplings we described for the electric blanket create a "round trip," or **feedback loop,** between components (Figure 2-1c). *Feedback* is a self-perpetuating mechanism of change and response to that change. When you receive feedback from your friends, you are receiving their *re*action to an action of yours. Their reaction now becomes an action, and you *re*act to that action. You may modify your actions by either accentuating or suppressing them, and this modification will affect the nature of the subsequent feedback you receive. Consider Deb, who is Ed's employer. If Deb complains that Ed is dressing inappropriately at work, Ed may respond by dressing more conservatively, or he may instead dress the same or even more inappropriately. Either reaction (which is now an action) will undoubtedly cause a subsequent reaction—praise or criticism—from Deb. In terms of change and response, natural systems with feedback loops behave in a similar manner.

The feedback loop in the electric blanket example is referred to as a **negative feedback loop.** Negative feedback loops tend to diminish the effects of disturbances. An increase in body temperature, however caused, stimulates you to turn down the controller on the blanket. The blanket subsequently radiates less heat, and your body temperature then decreases.

In contrast to negative feedback loops, **positive feedback loops** amplify the effects of disturbances. To understand positive feedback loops, consider another electric-blanket example based on a real-life episode in the life of former U.S. president Jimmy Carter (Figure 2-2). Jimmy and his wife, Rosalynn, had an electric blanket with dual controls—one for his side of the blanket and another for

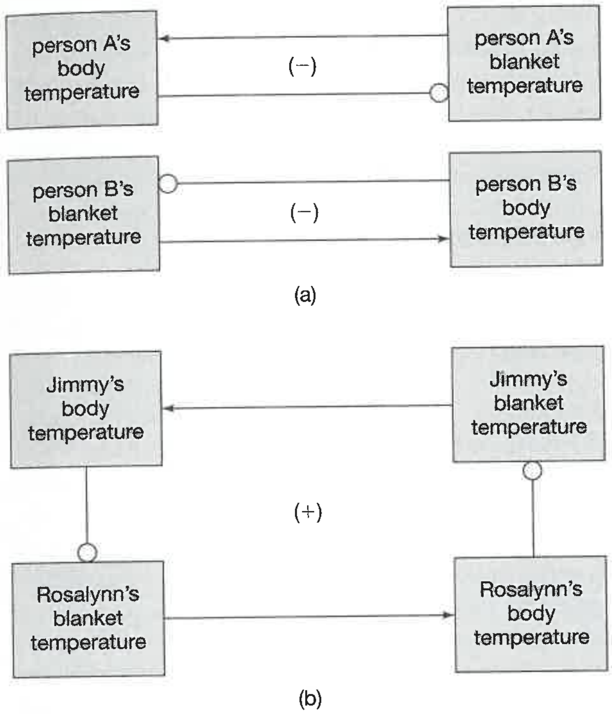


FIGURE 2-2 The consequences of combining feedback loops for a dual-control electric blanket. (a) Proper usage: Two independent, negative feedback loops. (b) Improper usage: A single positive feedback loop formed when the Carters inadvertently exchanged temperature controllers.

hers. In his autobiography, President Carter describes the irritation they were suffering:

> During each of the increasingly cold winter nights, we argued about the temperature of our electric blanket. Whenever I said it was too warm, Rosalynn said it was too cold, and vice versa.
>
> One morning I returned from an overnight trip to New York, and she met me at the front door with a warm hug and a smile. "I think our marriage is saved," she said. "I just discovered that our dual blanket controls have been on the wrong sides of the bed, and each of us was changing the temperature on the other's side." (Jimmy Carter, *Living Faith,* New York: Random House, 1996, p. 74.)

If the Carters had been thinking like systems scientists, the reason for their troubles would have immediately been obvious. A systems diagram for the proper use of the blanket is shown in Figure 2-2a. With their own controllers in hand, both persons would adjust their own blanket setting. If either person becomes chilly, he or she turns up the blanket controller and soon returns to a comfortable body temperature.

By inadvertently switching their temperature controllers, the Carters created a single, but more complicated, four-component feedback loop involving both controllers (Figure 2-2b). The new loop is positive, consisting of two positive and two negative couplings. If Jimmy gets a bit warm, he unwittingly turns down Rosalynn's controller. She begins to feel a chill and so turns up what she thinks is her controller (but is actually Jimmy's). Jimmy gets even warmer, and then turns down Rosalynn's controller even further! This runaway response is characteristic of positive feedback loops.

A simple way to identify the "sign" of a feedback loop is to count the number of negative couplings. Negative feedback loops have an odd number of negative couplings; the rules of multiplication apply here. Recall that when two positive numbers are multiplied, the result is a positive number. When two negative numbers are multiplied, the result is also a positive number. But when a positive number and a negative number are multiplied, the result is always a negative number. Thus, if there is an odd number of negative couplings in a feedback loop, the loop is negative. If there are no negative couplings or an even number of them, the loop is positive.

Equilibrium States

The normal electric-blanket feedback loop (Figure 2-1c) acts to maintain body temperature (defining the state of the system) within a comfortable range. If your body temperature is just right, you do nothing to the blanket controller. We refer to this condition as an **equilibrium state** of the system; it will not change unless the system is disturbed. Because this state is created by a negative feedback loop, the equilibrium state is said to be **stable**: Modest disturbances from this state will be followed by system responses that tend to return the system to its equilibrium state. The equilibrium state of comfort for the Carter's feedback loop (Figure 2-2b) was **unstable**: The slightest disturbance from a comfortable state led to system adjustments that carried the system further and further from that state.

To visualize equilibrium states better, we can represent all the possible states of a system as a hilly surface and the present state as a ball that is free to move on that surface (Figure 2-3). The valleys represent stable equilibrium states, and the peaks represent unstable equilibrium states. After a small disturbance, a ball in a stable equilibrium state will roll back down the hill and return to its original state (Figure 2-3a). Valleys, or regions of stability, are defined by the peaks that surround them. A large disturbance—large enough to roll the ball out of its valley and over an adjacent peak—can carry the system to a different equilibrium state (Figure 2-3b). Thus, there are limits to the stability of stable equilibrium states.

In contrast, an unstable equilibrium has no region of stability. A ball disturbed ever so gently from its "resting" point at the top of a peak will roll down the hill and will land in a valley (Figure 2-3c). On its own, the ball will not return to its original state. The slightest disturbance pushes the state of the system toward a new *stable* equilibrium (if one exists).

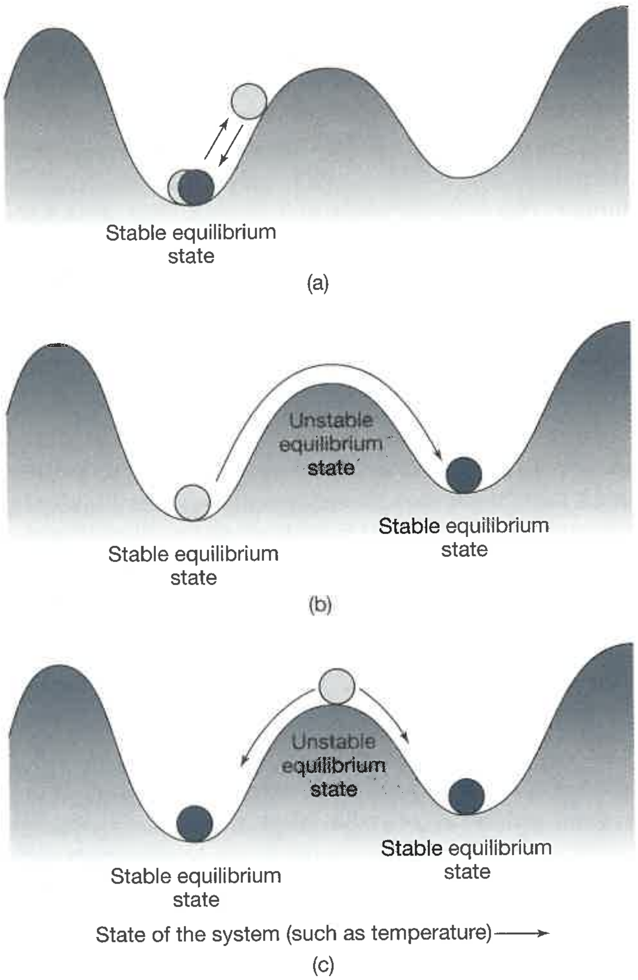


FIGURE 2-3 The equilibrium states of a system, represented as peaks (unstables) and valleys (stables). On disturbance, the system returns to stable equilibrium states but moves away from unstable equilibrium states.

It is unlikely that a given system would remain poised for any length of time at an unstable equilibrium state.

It appears that a system with a single feedback loop has a stable equilibrium state if the feedback loop is negative and an unstable equilibrium state if the feedback loop is positive. This conclusion is usually true, at least for the natural systems we will be discussing in this book. (See the Box "Thinking Quantitatively: Stability of Positive Feedback Loops" for a discussion of conditions under which positive feedback loops can create stable equilibrium states.) However, in reality, natural systems tend to be combinations of subsystems involving both positive and negative feedback loops. Stability cannot be easily determined by simply inspecting the feedback diagrams of such systems. Rather, they need to be analyzed mathematically.

Perturbations and Forcings

We can learn much by observing how a system responds to disturbances. Our understanding of human physiology, for example, has benefited from the study of patients stricken by illness or accident. The Carters learned about the problem with their electric-blanket system when their body temperatures were disturbed. Similarly, scientists are learning about the Earth system by watching how it responds to disturbances. For example, Earth's climate system is being modified by a variety of natural and anthropogenic factors. One such **perturbation,** or temporary disturbance of a system, is the injection of sulfur dioxide (SO_2) into the atmosphere during volcanic eruptions. Over several weeks, SO_2 reacts to form sulfate aerosol particles (like those formed by the burning of fossil fuels; see Chapter 1) that prevent a small amount of sunlight from reaching Earth's surface. As a result, surface temperatures drop by a bit less than 0.5°C (1°F) globally (Figure 2-4). The climate system recovers from this perturbation several years later as the sulfur is naturally removed from the atmosphere. Because of natural climate variability it is difficult to conclusively ascribe a cool interval following a particular volcanic event to the eruption itself, so Figure 2-4 presents the average climatic response to the five largest eruptions of the last century or so.

A more persistent disturbance of a system is called a **forcing.** In Chapter 1 we mentioned one forcing of Earth's climate: the gradual increase in the amount of sunlight Earth has been receiving over billions of years. How has the climate responded to this forcing? Many scientists argue that the tendency toward surface temperature rise that has accompanied the increased sunlight has been countered by a decrease in atmospheric CO_2 concentrations, reducing the greenhouse effect and thereby cooling the surface.

Understanding the response of the Earth system to forcings such as this is a major focus of this book. Rather than begin with the complex Earth system, however, we will consider the much simpler climate system of the hypothetical

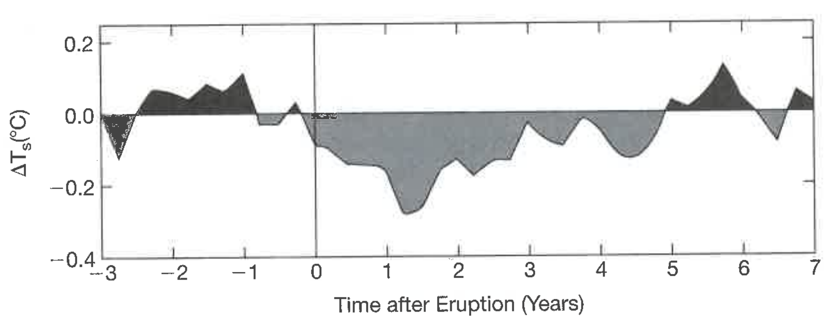


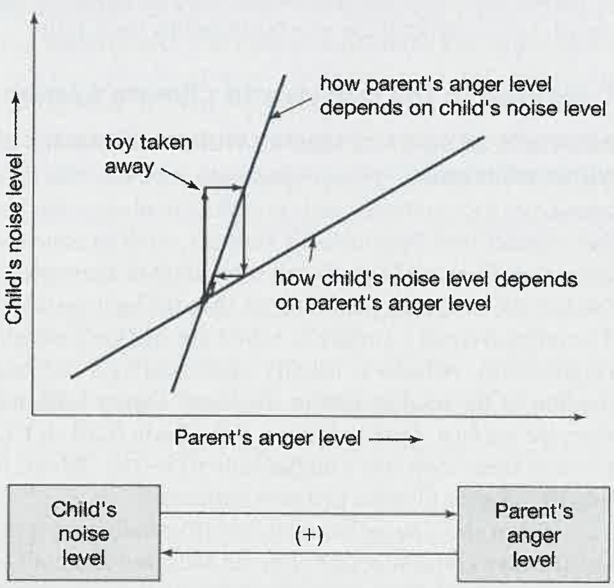
FIGURE 2-4 The average climatic response to the five largest volcanic eruptions of the last 120 years: Krakatau (1883), Santa Maria (1902), Agung (1963), El Chichon (1982), and Pinatubo (1991). (*Source:* Courtesy NASA.)

THINKING QUANTITATIVELY:

Stability of Positive Feedback Loops

Although most isolated, positive feedback loops are unstable, stable equilibrium states can exist for positive feedback loops if the state of one component depends only on the current state of the other component (that is, the adjustment of the state of the system is instantaneous rather than incremental). Suppose a child's noisiness increases as the parent gets angrier, and the parent's anger increases as the child's noisiness increases, creating a positive feedback loop. This loop may be stable if the adjustments in anger level and noisiness are instantaneous, modest, and depend only on the current state of one another. For example, the child starts whining when a toy is taken away. The parent will become angry, but the child, having forgotten about the toy and now responding solely to the anger of the parent, may actually become quieter if the anger is moderate. As the child quiets, the parent's anger diminishes, and peace is restored (Box Figure 2-1).

Most natural systems do not behave in this way, however. The components of natural systems are generally *accumulators* or *reservoirs* of energy or mass, and their response depends not just on the immediate stimulus, but on the accumulation of past stimuli as well. Their response is also time-dependent: Their states do not respond immediately to a stimulus; instead, they do so over some interval of time. Equilibrium states characterized by positive feedback in such systems are always unstable. In the previous example, if the child's anger had been cumulative, the anger of the parent would simply have made the child noisier, and the situation would have escalated out of control.



BOX FIGURE 2-1 In this system, the parent and child respond to each other's state instantaneously. The system is disturbed from its equilibrium state when the parent takes a toy away from the child. The child's noisiness increases, which causes an increase in the parent's anger level. In response, the child's noisiness actually diminishes because the parent's response elicits a noise level in the child that is less than its original perturbed level. As the child's noisiness diminishes, the parent's anger level diminishes until equilibrium is restored. The equilibrium state is stable despite being characterized by positive feedback in this special case where the parent and the child respond solely to the instantaneous state of the other. This is not true of most natural systems, and we cannot use this type of diagram to conclusively demonstrate the stability or instability of natural systems.

As mentioned in the text, a true test of system stability must be performed mathematically. Because most natural systems are time-dependent, their behavior must be described by differential equations. Differential equations are beyond the level of most readers of this book; however, readers who have the required mathematical background are invited to follow the discussion below.

Suppose we have a system of two reservoirs whose states (e.g., amounts of material in the reservoirs) are represented by the variables $A(t)$ and $B(t)$, which are coupled in a feedback loop. Furthermore, suppose that an equilibrium state exists in this system, in which the reservoir sizes are denoted by A_{eq} and B_{eq}. We are interested in how these reservoirs will respond to a disturbance from their equilibrium state. This system can be described by the following two differential equations:

$$dA/dt = a\,(B - B_{eq})$$
$$dB/dt = b\,(A - A_{eq}).$$

Here, a and b are constants. The feedback loop is positive if both a and b are positive or if both constants are negative. If a and b have opposite signs, the feedback loop is negative. This follows from our definition of positive and negative couplings. A coupling is positive if component A responds in the same direction as the perturbation to component B; it is negative if the response is in the opposite direction.

The solution to these two coupled differential equations can be shown to be

$$A(t) - A_{eq} = \left\{\frac{(A_0 - \beta B_0)}{2}\right\}\exp(\alpha t) + \left\{\frac{(A_0 - \beta B_0)}{2}\right\}\exp(-\alpha t).$$

Here, A_0 and B_0 are the amounts that A and B are disturbed from their equilibrium values at the initiation of the disturbance, and $\alpha = \sqrt{ab}$ and $\beta = \sqrt{\frac{a}{b}}$. The second term on the right-hand side has a negative exponent and thus decays with time, but the first term has a positive exponent and thus will increase without limit as time progresses if α is a real number. Thus, if the product ab is positive, as it must be for a positive feedback loop, the system is clearly unstable. When a and b have opposite signs, though, as they do in a negative feedback loop, then the product ab is negative. The square root of a negative number is imaginary, so α is no longer a real number. In such a case, the system becomes a sinusoidal oscillator. The solution is always bounded, however, thus demonstrating that negative feedback loops are stable.

planet Daisyworld. This planet, whose only life-forms are daisies, derives from the creative imaginations of James Lovelock (who, with Lynn Margulis, originated the Gaia hypothesis; see Chapter 1) and his colleague Andrew Watson, an oceanographer. When the Gaia hypothesis was first proposed, a common criticism was that the biota would need to possess the capacity for foresight or planning if the Earth system were to be self-regulating (for example, able to prevent large fluctuations in the surface environment). Lovelock and Watson used Daisyworld to demonstrate that natural systems can be self-regulating on a global scale without the need for intelligent intervention. Let us see how.

THE DAISYWORLD CLIMATE SYSTEM

Imagine that the year is A.D. 2150. We have just determined that there is life on a nearby planet and have sent a manned mission there. On their arrival, the mission scientists observe that the planet is indeed supporting life, but only what appear to be daisies. Hence the scientists name the planet Daisyworld. These daisies are unusual, however: They are pure white in color. They appear to be getting their nutrients and water from the soil; the atmosphere has no clouds and no greenhouse gases. The daisies cover vast regions of the planet's surface; the rest of the surface is mantled in gray soil (Figure 2-5). This means that the amount of sunlight absorbed by the planet depends on the area of darker, bare soil relative to the area of lighter daisy cover. The more sunlight absorbed, the higher the surface temperature. Experiments carried out by the mission scientists show that the growth and spread of daisies across the planet's surface depends only on the temperature around them.

FIGURE 2-5 A view of Daisyworld from outer space.

The mission scientists are alarmed because the planet's sun seems to be increasing in luminosity at a much faster rate than is our own Sun. They calculate that the planet will quickly become too hot to support daisy growth. However, they make this calculation without considering that the daisies are part of a global climate system in which the reflectivity of the planet is affected by any change in the daisy population. Might a systems approach yield a different prediction for the survival of daisies on Daisyworld in the face of an increasingly luminous sun?

We can represent the Daisyworld climate system on the global scale as a two-component system. One component is the area of white-daisy coverage, and the other is the average surface temperature of the planet. These two components form a system because they are interdependent: The extent of daisy coverage affects the surface temperature, and the surface temperature affects the growth rate of daisies, which in turn affects the daisy coverage of the planet. Let's explore these interrelationships more fully.

Couplings in the Daisyworld Climate System

RESPONSE OF SURFACE TEMPERATURE TO CHANGES IN DAISY COVERAGE From experience, we know that on a sunny day, dark surfaces, such as asphalt roadways, tend to feel warmer than light-colored surfaces, such as concrete sidewalks. Dark surfaces absorb more (that is, they reflect less) of the incoming solar energy than do light surfaces. The reflectivity of a surface is called the surface's **albedo** (Figure 2-6). Albedo is usually expressed as a decimal fraction of the total incoming (*incident*) energy reflected from the surface. Dark soil has a low albedo (0.05–0.15), whereas fresh snow has a high albedo (0.8–0.9). Table 2-1 lists the albedos of some common surfaces.

From the limited amount of information we have about Daisyworld, together with our intuition about albedo, we can graph the relationship between daisy coverage and surface temperature—in other words, the effect that

TABLE 2-1 Albedos of Some Common Surfaces

Type of Surface	Albedo
Sand	0.20–0.30
Grass	0.20–0.25
Forest	0.05–0.10
Water (overhead Sun)	0.03–0.05
Water (Sun near horizon)	0.50–0.80
Fresh snow	0.80–0.85
Thick cloud	0.70–0.80

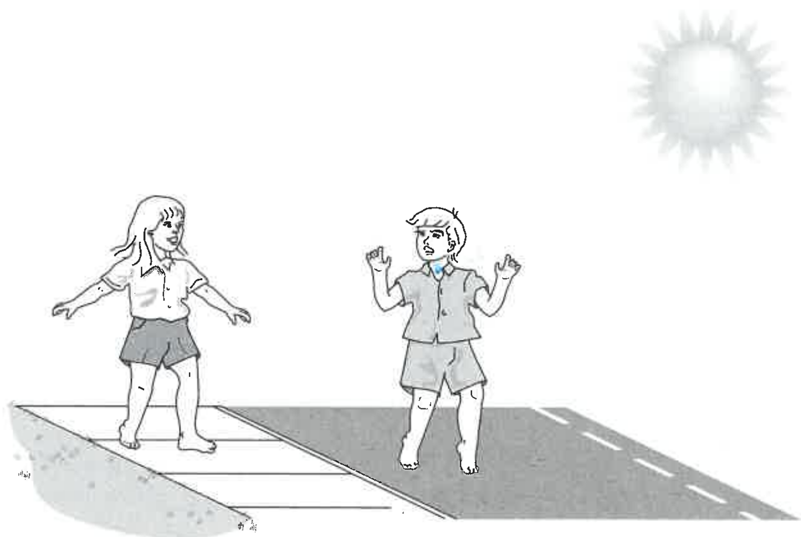


FIGURE 2-6 A visual comparison of high-albedo and low-albedo surfaces. Light-colored surfaces are more reflective (that is, have a higher albedo) than dark surfaces, which absorb more sunlight.

changes in daisy coverage has on temperature. Refer to the box "Graphs and Graph Making." We know that the surface temperature on Daisyworld is determined by the amount of daisies that cover the surface: The more daisies, the more sunlight reflects off their white petals, the less sunlight absorbed, and finally the cooler the surface temperature. The graph should have a *negative slope* (that is, "runs downward" from left to right), reflecting the fact that as daisy coverage increases, temperature decreases (Figure 2-7a). We *cannot* interpret the graph in Figure 2-7a to mean, however, that as surface temperature drops, daisy coverage rises linearly. The way changes in surface temperature affect daisy coverage on Daisyworld is *not* the same as the way changes in daisy coverage affect surface temperature.

This graph can also be expressed as a coupling that links white-daisy coverage to temperature (Figure 2-7b). The coupling is negative: An increase in daisy coverage causes a decrease in surface temperature, and a decrease in daisy coverage causes an increase in temperature. Note that the "sign" of this coupling—negative—matches the sign of the slope in the graph.

Thus far in our discussion, the albedo of the planet has been a component of the Daisyworld climate system that we have treated only implicitly. However, we could treat albedo *explicitly* by adding it as a third component. The coupling that describes the effect of changes in white-daisy coverage on temperature is now seen as the combination of a positive and a negative coupling that links daisy coverage, albedo, and temperature (Figure 2-8). Decreased white-daisy coverage leads to a reduction in the average albedo (a positive coupling), and reduced albedo causes an increase in temperature (a negative coupling).

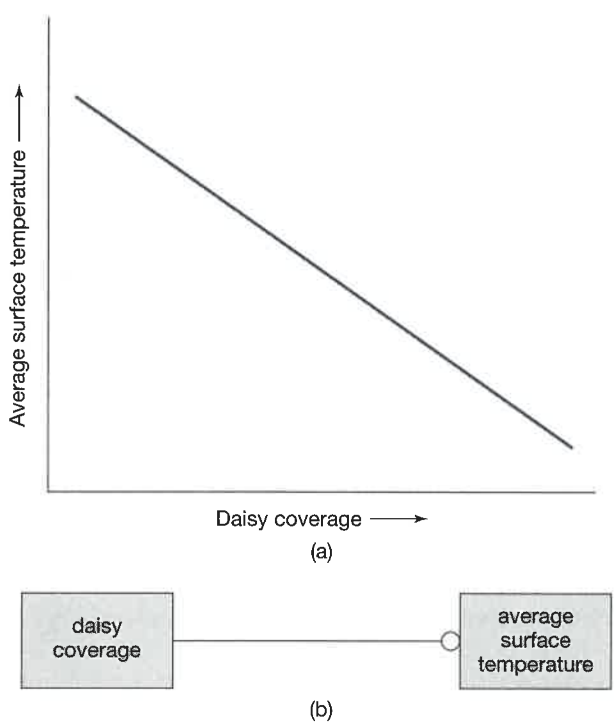


FIGURE 2-7 (a) Graph and (b) systems diagram of the effect of changes in white-daisy coverage on Daisyworld surface temperature.

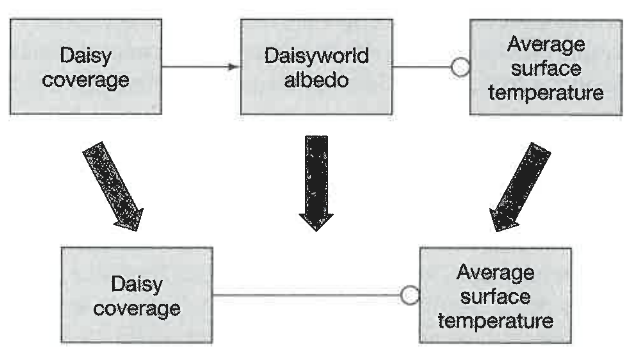
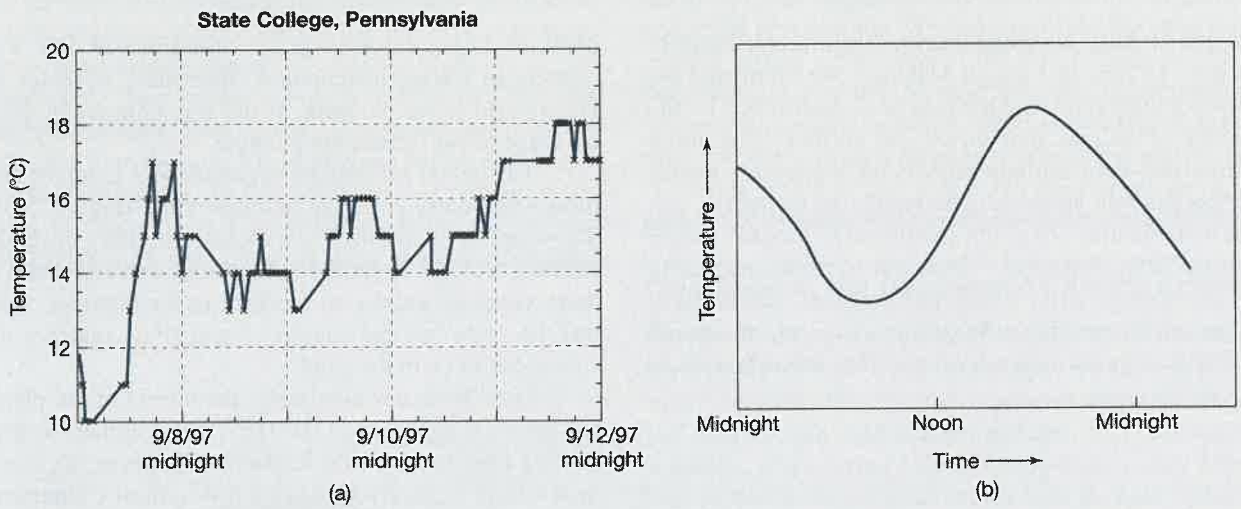


FIGURE 2-8 The same overall coupling as that in Figure 2-7b, but with albedo shown explicitly. A positive and a negative coupling combine to form a negative coupling overall.

USEFUL CONCEPTS:
Graphs and Graph Making

Graphs are a powerful way to convey scientific information in an economical way. If a picture is worth a thousand words, a graph can be worth a thousand data points. There are a number of ways in which graphs are used in science, and we present many of them in this textbook. All graphs convey information about the relationship between two (or more) variables. (*Variables* represent any number value.) In a conventional $x - y$ graph, data are plotted with the *independent variable* on the x-axis and the *dependent variable* on the y-axis. The value of the dependent variable depends on the value of the independent variable, but the converse is not true. For example, a graph showing hourly measurements of temperature over the course of several days at a particular place would plot temperature, the dependent variable, as a function of time, the independent variable (Box Figure 2-2a).

Graphs can be used to convey the sense of relationships even when data are not available. We may, for example, convey the notion that temperature varies more or less regularly from day to night with a sketch such as Box Figure 2-2b. We make it clear that no data are being plotted by plotting only a smooth curve; in labeling the axes for such a graph, we do not even show the scale of the graph. In other cases we may wish to put some bounds on the axes, but it would be misleading to place numbers on the axes in a graph for which actual values are not available.



BOX FIGURE 2-2 Examples of various uses of graphs. (a) Display of data: temperature measurements made at State College, Pennsylvania, during a three-day period. (b) Conveying a concept with no data: sinusoidal daily temperature variation.

When combined, the two couplings in Figure 2-8 form a negative coupling overall, like that shown in Figure 2-7. The rule for combining couplings is the same as the rule for determining the sign of feedback loops. The explicit treatment of albedo, therefore, does not change our conclusion regarding the overall sign of the coupling. For convenience and simplicity, then, we will often treat such couplings implicitly.

RESPONSE OF DAISY COVERAGE TO CHANGES IN TEMPERATURE In comparison with real daisies, we expect that Daisyworld daisies have an upper and lower temperature limit for survival. They must also have an *optimum,* or most favorable, temperature somewhere in between (let's specify that it is halfway between, for simplicity). A smooth curve drawn through these points is a *parabola* (Figure 2-9). The parabola is a characteristic shape for the temperature dependence of many plants on Earth. It intuitively makes sense that the abundance of an organism would be highest near the organism's optimum temperature and would drop to zero at the upper and lower limits of that organism's temperature range.

The sign of the coupling that reflects the response of daisy coverage to temperature changes depends on temperature, because the relationship is parabolic, as Figure 2-9 shows. If the temperature is below the optimum value for daisy growth, the coupling is positive. If the temperature is above the optimum value, the coupling is negative. This pattern is consistent with the slope of the parabola in Figure 2-9, which has opposite signs on either side of the optimum growth temperature for white daisies.

Equilibrium States in Daisyworld

We can determine the equilibrium states of Daisyworld by combining Figures 2-7 and 2-9. But note that temperature and daisy coverage are on opposite axes, so we cannot

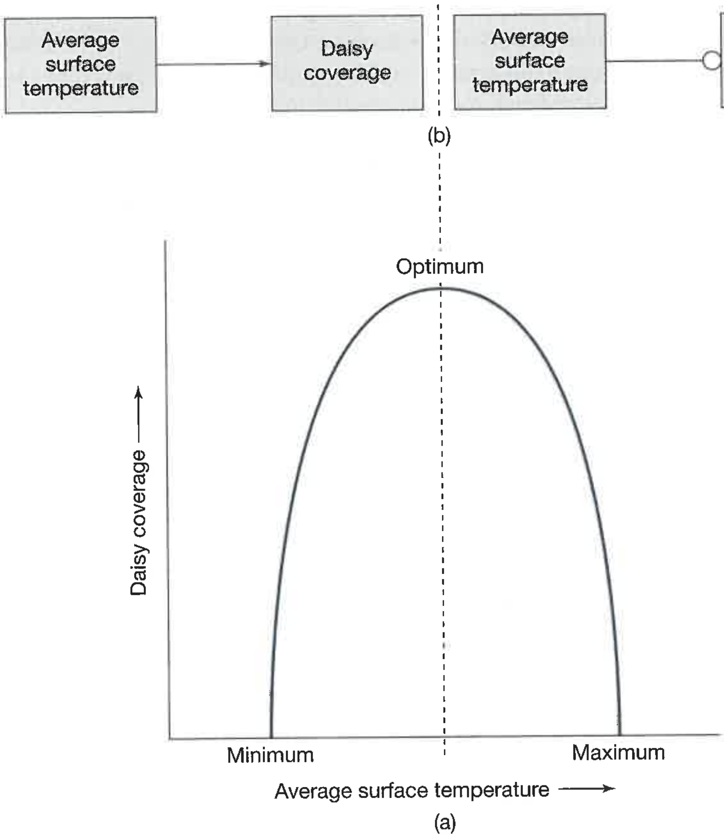


FIGURE 2-9 (a) Graph and (b) systems diagram of the effect of changes in Daisyworld surface temperature on white-daisy coverage.

simply overlay the plots. Instead, we must invert the axes of Figure 2-7. This inversion does not change the nature of the coupling, it simply interchanges the positions of the two variables so that the axes will match up when we overlay the two graphs.

We can now overlay the two graphs (representing the two couplings); the resulting graph is shown in Figure 2-10a. The curves intersect at two points, labeled P_1 and P_2. These points of intersection are special because they represent the only states of the system that simultaneously fall on the curves showing both the effect that white-daisy coverage has on surface temperature *and* the effect that surface temperature has on white-daisy coverage. For example, at any point other than P_1 or P_2 on the parabola, the effect of temperature on daisy coverage is properly characterized, but the effect of daisy coverage on temperature is not. Conversely, at any point other than P_1 or P_2 on the straight line, the effect of daisy coverage on temperature is right, but the effect of temperature changes on daisy coverage is not.

Points P_1 and P_2 are the equilibrium states of this system, because they represent the states at which the system is said to be in *equilibrium.* If the system is already in one of these states, it will remain there unless something disturbs it. Note that neither equilibrium state corresponds to the optimum temperature.

But how will these equilibrium states respond to perturbation? We can evaluate the stability of these states by constructing the systems diagrams for Daisyworld (Figure 2-11). Two feedback loops characterize the Daisyworld climate system—one that applies *below* the optimum temperature, to equilibrium state P_1, and another that applies *above* the optimum temperature, to equilibrium state P_2. The diagram applicable below the optimum has a positive and a negative coupling and is thus a negative feedback loop. The feedback loop applicable above the optimum has two negative couplings and is thus a positive feedback loop. Of the two equilibrium states, then, the one that is below the optimum temperature for daisy growth is stable, and the one that is above the optimum temperature for daisy growth is unstable.

Thus, the response of Daisyworld to perturbation depends on the temperature of the planet. At temperatures below the optimum for daisy growth, the system is characterized by negative feedback, which will tend to maintain the temperature and daisy coverage near a stable equilibrium state. (Note that the temperature is below the optimum for daisy growth.) If temperatures are perturbed above the optimum, the system will enter a region of positive feedback without a stable equilibrium state. If the perturbation is small, the temperature will return to the cool, stable equilibrium state below the optimum. Larger perturbations will carry the system over the edge of the stable equilibrium state's "valley" (Figure 2-10b), and temperatures will rise above the limits for daisy growth; the daisies die.

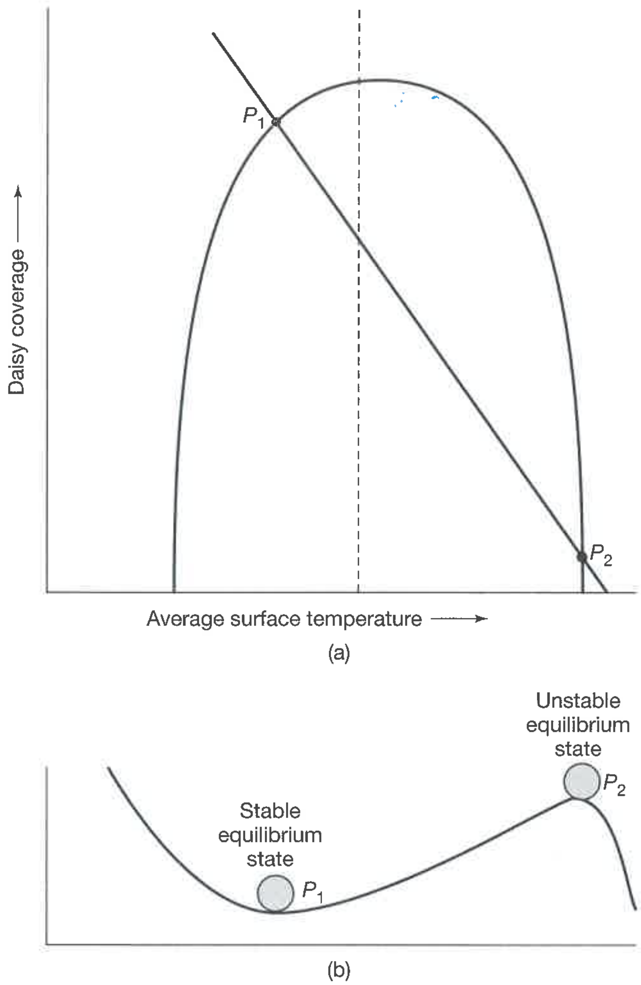


FIGURE 2-10 (a) The mutual influences of average surface temperature on white-daisy coverage (the parabola) and white-daisy coverage on surface temperature (the straight line). The intersection points (P_1 and P_2) are the equilibrium states of the system. (b) The stability of P_1 and instability of P_2.

EXTERNAL FORCING: THE RESPONSE OF DAISYWORLD TO INCREASING SOLAR LUMINOSITY

We have been investigating the behavior of the Daisyworld climate system by perturbing it from its equilibrium states and analyzing its response. Many of the disturbances we will be discussing in later chapters, however, are persistent forcings that can be considered *external* to the system. The response of systems to forcings can be quite different from that to perturbations because the system may not be able return to an original, stable equilibrium state even if negative feedback loops predominate.

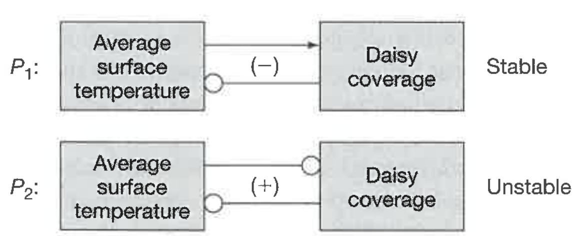


FIGURE 2-11 Feedback loops appropriate for small perturbations from equilibrium states P_1 and P_2, respectively.

The forcing on Daisyworld is the increase in solar luminosity recognized by the mission scientists. How will the climate system respond? Will the temperature rise quickly on Daisyworld, as the scientists predicted, spelling the end for daisies, or will the climate system respond in such a way to forestall the realization of this ultimate catastrophe?

On the basis of our experience about the ability of systems with negative feedback loops to damp perturbations, we might suspect that the system should act to extend the duration of the daisy inhabitation of the planet. Think of how the system would respond to a single, small but permanent increase in solar luminosity. The immediate response would be a warming of the planet's surface. This response, however, would be quickly followed by the spread of daisies, which, by increasing the albedo, would reduce the warming. A new equilibrium state would eventually be achieved at a temperature warmer than the original temperature. Yet it would be cooler than the temperature the planet would have achieved had the daisies not responded to the change in temperature and thereby altered the planet's albedo. Applying this line of reasoning to the problem at hand, we conclude that a persistent trend of increasing solar luminosity should lead to a gradual evolution of the equilibrium temperature of the planet to higher and higher temperatures, but at a rate that is slower than the warming that would otherwise occur in the absence of the feedback between the daisies and their environment.

Response of Daisyworld Couplings to Forcing

To predict the future climate of Daisyworld more accurately, we need to understand how the increasing intensity of Daisyworld's sun will affect the couplings in the system. Because we are assuming that the daisies respond only to temperature changes and thus not to changes in the solar luminosity itself, we would *not* expect modification of the coupling that links surface temperature changes to white-daisy coverage (the parabola in Figure 2-9). As the sun becomes more intense, surface temperature will rise, and the percentage of daisy coverage will respond according the parabolic curve, as before. However, we *would* expect a change in the coupling that relates surface temperature to the extent of daisy coverage (the straight line in Figure 2-10a). For any amount of daisy coverage, the surface temperature will increase as the intensity of the sun increases. This is not to say that the temperature will rise indefinitely. Rather, for any particular value of daisy coverage, the temperature will be higher than expected from Figure 2-7. The graphical result is that the line in Figure 2-7 shifts upward as solar luminosity increases (Figure 2-12).

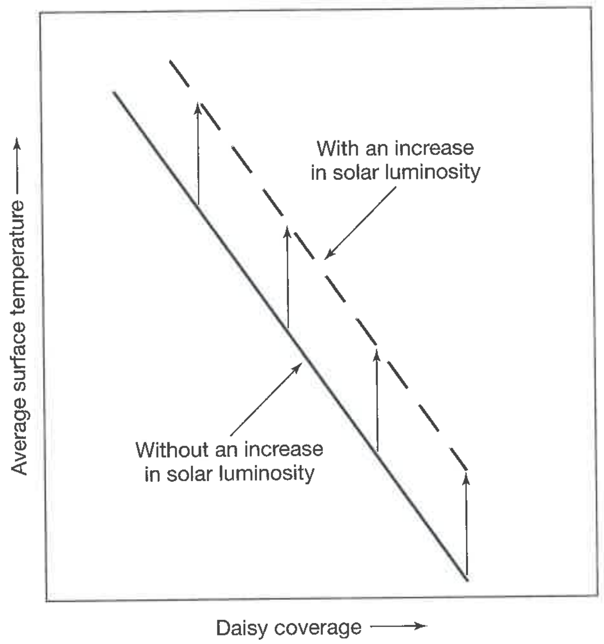


FIGURE 2-12 The effect of an increase in solar luminosity on the dependence of average surface temperature on white-daisy coverage. If the daisy coverage were fixed at a certain percentage, temperature would simply increase as shown by the arrows.

Response of Equilibrium States to Forcing

Let us again consider the response to an incremental increase in solar luminosity. If we combine Figures 2-9 and 2-12, we find, as before, that two equilibrium states exist (labeled P_1' and P_2' in Figure 2-13a). We can guess that, as before, only one of them will be stable, because the diagram has not changed fundamentally. Which one is it? The temperature at point P_1' is below the optimum growth temperature for daisies, so this situation is similar to that for point P_1. The temperature at point P_2' is above the optimum temperature for daisies, so this situation is similar to that for point P_2. Thus, we determine that P_1' is stable and P_2' is unstable.

However, we see that both the temperature and the daisy coverage at the new stable equilibrium are higher. Daisyworld has apparently reacted to increased solar luminosity by increasing the daisy coverage. The accompanying increase in albedo explains why the temperature at the stable equilibrium did not rise as much as it would have without feedback. Note that the "ridge" that defines the stability limit for P_1' is lower than it was before. This new equilibrium state is apparently less resistant to perturbations; further increases in solar luminosity should eliminate the stable equilibrium state entirely.

We can determine the effectiveness of this feedback mechanism by comparing the equilibrium temperature changes with and without feedback. Without feedback—that is, without any change in the daisy coverage—the temperature change that results from the increase in solar luminosity is large. The temperature change without feedback is represented in Figure 2-13a as ΔT_0. (Recall from Chapter 1 that ΔT means the *change in temperature.*) With feedback, however, the temperature increase is smaller—but not zero. The temperature change of the new equilibrium state (with feedback) is represented as ΔT_{eq}, and the temperature change of the *feedback effect* itself is ΔT_f.

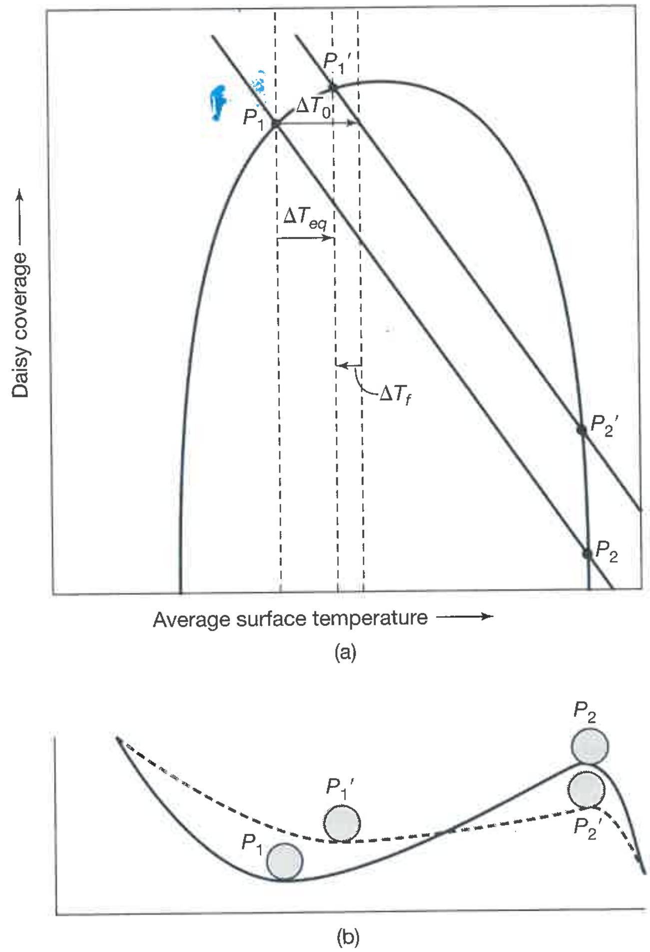


FIGURE 2-13 (a) Response of Daisyworld to an increase in solar luminosity. (b) The stability of P_1 and P'_1 and the instability of P_2 and P'_2.

We can express the behavior of the Daisyworld system mathematically:

$$\Delta T_{eq} = \Delta T_0 + \Delta T_f.$$

In other words, the overall temperature change that results from increased solar luminosity is the sum of the temperature change with no feedback and the temperature change due to feedback. In our case, ΔT_{eq} is smaller than ΔT_0; the temperature effect of the feedback ΔT_f is negative. We can see this in Figure 2-13a: The arrow that represents ΔT_f points to the left—the negative direction—instead of to the right. Although we derived this equation for Daisyworld, it is a general relationship that can be applied to any stable equilibrium in a system involving feedback loops: The change in state of a system as it moves from one equilibrium to the next is the sum of the state change that would result without feedback and the effect of the feedback itself.

To quantify the strength of the feedback effect, we can define a value f, called the feedback factor. The **feedback factor** is the ratio of the equilibrium response to forcing (the response with feedback) to the response without feedback. In our example, this ratio is as follows:

$$f = \frac{\text{temperature change with feedback}}{\text{temperature change without feedback}} = \frac{\Delta T_{eq}}{\Delta T_0}.$$

Here f is less than 1, because the equilibrium response is smaller with feedback than it would have been without feedback. The value of f is between 0 and 1 whenever the feedback loop is negative but greater than 1 if the feedback loop is positive. As we mentioned previously, systems with positive feedback loops are stable only if they contain negative feedback loops as well. The feedback factor, f, can be defined only for stable systems, such as Daisyworld at point P_1. At point P_2, there is no stable equilibrium, and hence ΔT_{eq} is not defined there.

Climate History of Daisyworld

So far in our presentation of Daisyworld, we have avoided the use of actual values of temperature, daisy coverage, and albedo. However, we can assign reasonable values to the graphs to calculate the climatic response of Daisyworld to increasing amounts of sunlight. To present the details of the calculation would be premature; we shall introduce the physical laws in the next chapter. Suffice it to say that the calculations were based on typical growth curves for real daisies (see Figure 2-9), reasonable albedos for white daisies (0.9) and for gray soil (0.2), and a solar input similar to Earth's that also increases with time.

Figure 2-14a shows the history of white-daisy coverage, and Figure 2-14b shows the temperature history of Daisyworld from the time of its formation until the end of daisy inhabitation of the planet. (In these graphs, solar luminosity is plotted on the x-axis instead of time itself; solar luminosity increases more or less linearly with time. Scientists often make such substitutions so that their plots can be generalized; in this case, the plot is correct no matter how fast the change in luminosity occurs.) The solid curve in Figure 2-14b represents the "actual" surface temperature change on the daisy-inhabited planet. The dashed curve in Figure 2-14b shows how that surface temperature would differ if there were no daisies (in other words, no life-forms and no feedback). In the early years, temperature increases relatively rapidly. However, once the surface temperature rises above the minimum temperature for daisy survival, the white daisies begin to spread across the planet's surface. Their growth tends to cool the planet by increasing its albedo, and so the rate of warming slows dramatically. The daisy coverage expands rapidly at first, and then more slowly, in response to these increases in temperature, which are much smaller than we would predict for a lifeless (daisy-free) planet or for a planet with daisies but no feedback (and thus constant albedo).

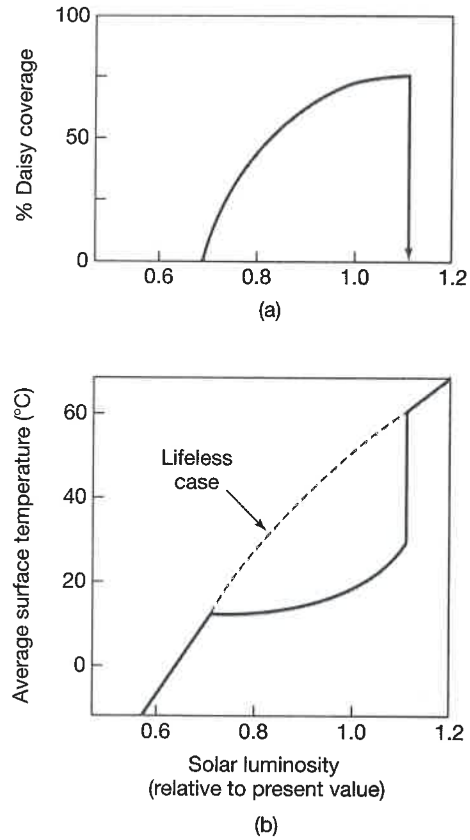


FIGURE 2-14 The response of Daisyworld to increasing solar luminosity. (a) The change in daisy coverage of the planet in response to changes in solar luminosity (relative to the presumed present value). (b) The change in average surface temperature of Daisyworld in response to increasing solar luminosity (solid line) and the response on a lifeless planet with fixed albedo (dashed line).

Eventually, as the temperature approaches the optimal temperature for daisy growth, daisy coverage too reaches its optimum (maximum). Once the optimum is reached, any further increase in solar luminosity cannot be countered by an increase in white-daisy coverage; in fact, daisy coverage decreases, so the planet's temperature begins to increase rapidly. The feedback loop becomes positive. Once this happens, the system becomes unstable: The surface temperature rises rapidly, and the daisies go extinct. Thereafter, because it is dictated by the lower albedo of the gray soil on the lifeless planet, the temperature overlays the dashed curve in Figure 2-14b. This is a good demonstration of *threshold behavior*; an observer charting the spread of daisies would not likely have anticipated that the asymptotic spread would be followed by a crash in daisy coverage, nor would he necessarily have anticipated the sudden jump in temperature based on the past history of temperature change.

The Lessons of Daisyworld

By studying the hypothetical planet Daisyworld from a systems perspective, we have learned some interesting things about climate systems in general. First, a planetary climate system is not passive in the face of internal or external influences. There are feedback loops that respond to perturbations and forcings (in this case, solar luminosity). Negative feedback loops in the system counter the external forcings. On Daisyworld, the consequence of this feedback is a longer life span for the daisies than one would predict if there were no feedback in the system. We will see in a later chapter that Earth's climate system has negative feedback loops as well that keep its climate relatively stable on both short and long time scales.

Second, the climate regulation system of Daisyworld, and, by analogy, other nonhuman systems that self-regulate, is seemingly intelligent: The response of the daisies is exactly what is needed to counter the solar warming of the planet. Yet no foresight or planning is involved. The daisies simply respond to the increase in temperature, and the planet's temperature responds to the spread of daisies. Such behavior is not restricted to contrived systems like Daisyworld. Indeed, self-regulation is a property common to many natural systems with feedback loops. Lovelock conceived of Daisyworld as a means of demonstrating to his critics that the Gaia hypothesis (which he applied to Earth) did *not* require an intelligent biota. Organisms can be components of self-regulating, natural systems simply because they influence, and are influenced by, the physical environment in which they live.

It is unlikely that the biota would be capable of optimizing their environment for their own good, as seemed to be required by the Gaia hypothesis when it was first proposed. The Daisyworld experiment indicates that it is not necessary for the biota to be capable of optimizing their environment. The Daisyworld system does not *optimize* the temperature for daisies. The stable equilibrium temperature is below the optimum for daisy growth on white-daisy Daisyworld.

Note that the self-regulation is not perfect. As the sun became more luminous, Daisyworld's climate system responded with a temperature increase, but the increase was much more gradual than would have occurred on a lifeless planet (or one with fixed daisy coverage). Systems like the Daisyworld climate system typically adjust to forcings by a slow but continual modification of their equilibrium states. This response is different from that directed by a thermostat, for instance, which is designed to maintain a constant state (temperature). In a natural self-regulating system, there is no preset state (no optimum value) that the system is programmed to "seek out."

An important lesson from Daisyworld is that thresholds often exist in systems, including the climate system, that when surpassed can lead to rapid changes in system state. These abrupt transitions may have no forewarning: The system may evolve slowly and modestly to a persistent forcing up to the point that the threshold is reached and dramatic change occurs. Or, more commonly in natural systems, a random perturbation of a system approaching a threshold can nudge it across the threshold, carrying the system into its new state "before its time."

The real Earth is not unlike Daisyworld: Its surface temperature has been maintained within the tolerance limits of living organisms for more than 3 billion years, despite substantial changes in solar luminosity. As on Daisyworld, the reason for the long-term stability of Earth's climate is the existence of strong negative feedback. The feedback loops that operate on Earth are, not surprisingly, more complicated than the one that operates on Daisyworld. As we will see, climate scientists have observed such threshold behavior in the climate system during particular intervals of Earth history. They are furthermore concerned that the modern climate system, forced by human activity, might be approaching a climate threshold that separates the relatively cool global climate from a much warmer, "greenhouse" state. Before discussing how Earth's climate system works, we will spend the next three chapters learning more about its components and their interactions.

Chapter Summary

1. Components of systems interact in ways that can either enhance or diminish the stability of the system.
   a. The components are linked by couplings, which can be either positive or negative.
   b. When couplings are arranged such that there is a round-trip flow of information, a feedback loop is formed. These feedback loops can be either positive or negative.
   c. Positive feedback loops amplify perturbations or forcings; negative feedback loops diminish them.
2. The presence of feedback loops leads to the establishment of equilibrium states.
   a. Negative feedback loops establish stable equilibrium states that are resistant to a range of perturbations; the system responds to modest perturbations by returning to the stable equilibrium state.
   b. Positive feedback loops establish unstable equilibrium states. A system that is poised in such a state will remain there indefinitely. However, the slightest disturbance carries the system to a new state.
3. The Daisyworld climate system is capable of resisting a warming trend induced by a sun that is becoming brighter with time.
   a. This capacity is the result of a negative feedback loop that involves the feedback between white-daisy coverage and temperature; it does not require foresight or planning.
   b. The key is the difference in albedo between the white daisies and the gray soil, together with the effect that temperature changes have on daisy growth and coverage.

c. Daisyworld has two equilibrium states, but only one is stable. This equilibrium state, in general, does not coincide with the optimum temperature for daisy growth.
d. The temperature response to an increase in solar luminosity can be thought of as a progression from one stable equilibrium state to the next. These equilibrium responses are the sum of the response that would occur without feedback plus the feedback effect itself. In the case of Daisyworld, the temperature change without feedback is larger than that from one equilibrium state to the next: The feedback effect is negative. Thus, the rate at which the planet warms is slower than it would be if there were no feedback between daisy coverage and surface temperature. The interval over which the planet is inhabited by daisies is extended because of the presence of feedback.

Key Terms

albedo
component
coupling
equilibrium state
feedback factor
feedback loop
forcing
negative coupling
negative feedback loop
perturbation
positive coupling
positive feedback loop
stable equilibrium
state
system
unstable equilibrium

Review Questions

1. A perturbation that causes a decrease in component *A* leads to a decrease in component *B*. Is the coupling between these two components positive or negative?
2. What is a feedback loop?
3. Why do negative feedback loops tend to diminish the effect of disturbances?
4. What distinguishes a forcing from a perturbation?
5. Are all equilibrium states stable? Why or why not?
6. What is albedo? How does it influence climate?
7. How are daisies on Daisyworld able to regulate the hypothetical planet's temperature?

Critical-Thinking Problems

1. In the Dysfunctia family, when the children get noisy, the parents get mad. When the parents get mad, the children get noisy. Draw a systems diagram for the Dysfunctia family.
   a. Is the feedback loop negative or positive?
   b. Is the family stable or unstable?

2. Earth's average temperature is determined in part by the amount of CO_2 in the atmosphere, by way of the greenhouse effect. The atmospheric CO_2 content may in turn be affected by the photosynthetic activity of plants, which convert CO_2 into plant tissue. However, the rate of photosynthesis depends on the amount of CO_2 in the atmosphere and on global air temperature. The components of this system—atmospheric CO_2 content, global temperature, and photosynthesis rate—are intimately interconnected. By increasing global photosynthesis rates, plants would tend to lower the atmospheric CO_2 level. In doing so, however, the plants would tend to cool Earth. This cooling, together with the reduced CO_2 level, might tend to reduce the photosynthetic activity of plants.
   a. On the basis of this discussion, draw a systems diagram of the photosynthetic rate–CO_2–temperature system.
   b. How many feedback loops are there?
   c. Are the feedback loops positive or negative?
   d. Describe the response of the system to the following perturbations:
      (i) an increase in atmospheric CO_2;
      (ii) a decrease in temperature.
   e. Extra credit: How might the system respond to a continuous forcing—an increase in solar luminosity through time?

3. White-daisy Daisyworld has a companion planet that is similar in all ways except that the daisies are black.
   a. What is the effect of an increase in black-daisy coverage on planetary temperature? Express your answer graphically.
   b. Assuming that the effect of temperature on daisy coverage is the same on black-daisy Daisyworld as on white-daisy Daisyworld, draw a *stability diagram*—a diagram analogous to Figure 2-10—for black-daisy Daisyworld. Include two equilibrium states.
   c. Which of the two equilibrium states in part (b) is stable?
   d. Is the stable equilibrium state of part (c) cooler or warmer than that of white-daisy Daisyworld?
   e. How would this system respond to a *decrease* in solar luminosity? Express your answer graphically and in terms of the feedback factor *f*.
   f. Is *f* of part (e) greater than or less than 1?

4. The lines and curves shown in the graphs of this chapter can be converted to mathematical expressions that relate the values on the y-axis to those on the x-axis. The equation that relates the average planetary temperature (T) to percentage of daisy coverage (C) in Figure 2-10 is

$$T = 56 - \frac{C}{2},$$

while the curve that characterizes the dependence of daisy coverage on temperature is

$$C = 90 - \frac{(22.5 - T)^2}{4}.$$

a. The equilibrium states are defined as the values of T and C where the two equations are equal. Find these equilibrium states.
b. Find the equilibrium states for the case of higher solar luminosity on Daisyworld (Figure 2-10). You will have to define a new equation for the line. (*Hint:* The slope is the same; only the y-intercept has changed.)

Further Reading

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