Chapter 10. Homeostasis (preview copy)

Homeostasis refers to our remarkable capability to maintain a relatively stable physiological state even when the outside environment is varying dramatically. This chapter explains homeostasis with examples from Walter Cannon's (1932) classic book on *The Wisdom of the Body*. It then turns to general ideas that may be useful beyond physiological systems. The chapter closes with a discussion of the *span of control* and its use in case studies in the book.

Homeostasis

The term *homeostasis* was invented by Walter Cannon, Professor of Physiology at the Harvard Medical School. Cannon was intrigued by how the body maintains a stable state. He believed higher organisms had "learned" this ability over eons through gradual evolution. Organisms have had large and varied experience in "testing different devices for preserving stability" in the face of potential dangers. As they have grown to become more complex, Cannon believed that it was imperative that they develop more "efficient stabilizing arrangements."

Cannon opened with the example of blood pressure, a topic of paramount importance because of the need to maintain adequate pressure for the blood to "perform as a common carrier of nutriment and waste and to assure an optimum habitat for living elements" (Cannon 1932, 41). Cannon explains the physiological responses to blood loss in great detail. This chapter combines his descriptions with information from a standard text on medical physiology (Guyton & Hall 1996) to provide a concrete example of homeostasis, feedback and the span of control.

Blood Pressure Control

Causal loop diagrams are a useful way to summarize some of the physiological responses to a disturbance in blood pressure. Fig. 10.1 provides a start with the size of an initial cut or rupture that opens a wound. A larger cut leads to a larger wound and greater blood loss. The body quickly senses the trauma to the local vessels and triggers a vascular spasm which acts to reduce the size of the wound.

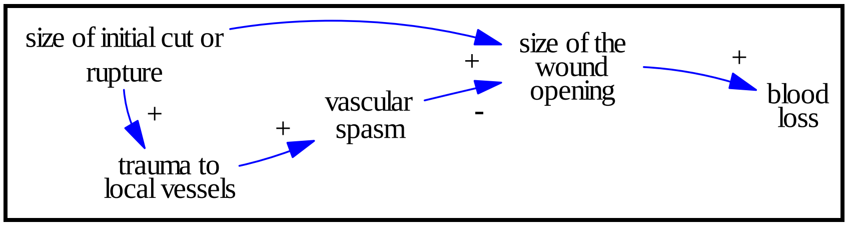

Fig. 10.1. External disturbance leads to a wound and blood loss.

The vascular spasm helps reduce the blood loss, but the body's main response is clot formation. A blood clot is composed of a meshwork of fibrin fibers which run in all directions, entrapping blood cells, platelets and plasma. These fibers adhere to damaged surfaces of blood vessels, so the blood clot adheres to the vascular opening, reduces the size of the wound, and lowers the blood loss.

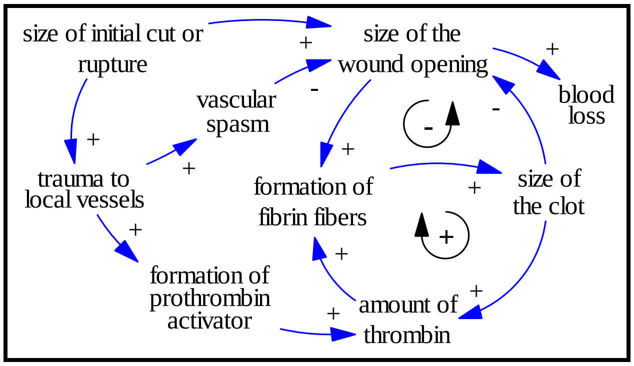

Fig. 10.2. Feedback effects for clot formation.

Fig. 10.2 summarizes some of the factors in clot formation. It begins with trauma to local vessels and the formation of the prothrombin activator, which is said to be the rate-limiting factor in causing blood coagulation. This leads to more thrombin production and greater formation of fibrin fibers which add to the size of the clot. As the clot grows, there is still greater formation of thrombin and more formation of fibrin fibers and a larger clot. Guyton & Hal (1996, 466) describe the process of rapid clot formation:

> *Once a critical amount of thrombin is formed, a vicious circle develops that causes still more blood clotting and more thrombin to be formed: thus, the blood clot continues to grow until something stops its growth.*

It's the final closure of the wound that eventually stops the growth in the blood clot, as shown by the negative feedback loop in Fig. 10.2.

Now let's look to the question of how the body responds in the minutes following the loss of blood. It is crucial that the body maintain blood pressure during this dangerous time Cannon describes several responses that act to prevent loss of blood pressure. Two of the responses act through the muscles and the spleen, as shown on the right side of Fig. 10.3.

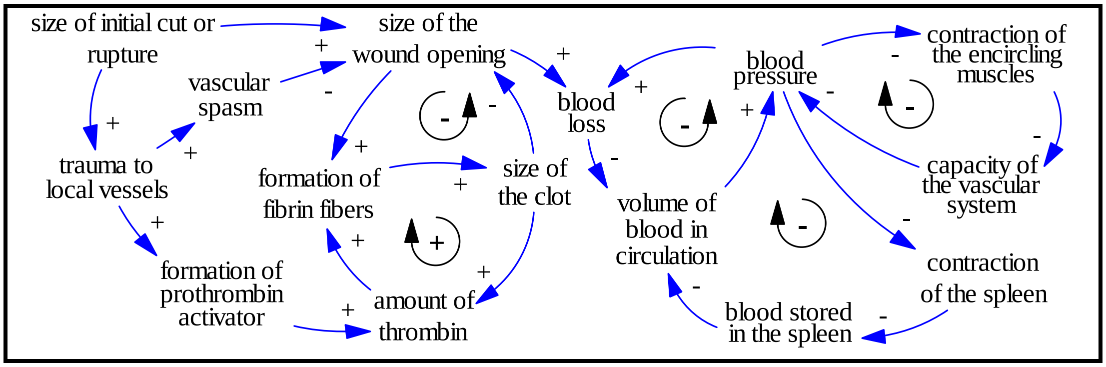

Fig. 10.3. Additional loops working to control blood pressure.

The loop in the upper-right corner involves the muscles that encircle the vascular system. A decline in blood pressure causes these muscles to contract, and their contraction reduces the capacity of the vascular system. Lower capacity means higher blood pressure, so this loop acts to maintain blood pressure in the face of cumulative blood loss. The loop in the lower-right corner of the diagram works through the spleen. The spleen is a reservoir of blood, and a drop in blood pressure may trigger the spleen to contract. The contraction releases the stored blood into the general vascular system, and the extra blood adds to the total volume of blood in circulation and increases the blood pressure.

Discussion of Blood Pressure Control

These responses illustrate a general point about physiological systems --- the majority of the feedback in physiology systems takes the form of negative feedback. Indeed, Guyton & Hall (1996, 8) explain that "essentially all control systems of the body operate by negative feedback." They argue that positive feedbacks generally "lead to instability, and often death." But, fortunately, there are "rare instances" (like clot formation) where the "body has learned to use positive feedback to its advantage."

Cannon's description of blood pressure control is followed by descriptions of the control of blood sugar, food intake, water intake and salinity. At first glance, these systems may appear to be entirely different in design and composition. But Cannon saw that they were fundamentally the same when viewed in terms of their ability to maintain homeostatic control within a tolerable range. Physiologists now summarize the effectiveness of the control mechanisms by the normal range (i.e., 98 to 98.8 ºF) and the approximate non-lethal limits (i.e., 65 to 110 ºF).

The effectiveness of homeostatic systems can also be described by their ability to survive a major disturbance. In the case of blood loss, for example, Guyton & Hall (1996, 8) estimate that the normal body can lose around a liter of blood and still survive. The body's ability to survive a major disturbance is often discussed in terms of the span of control, a key concept when we discuss how Cannon's ideas could transfer beyond physiological systems.

Beyond Physiology

In the epilogue to *The Wisdom of the Body*, Cannon (1932, 287) asks if there are general principles of stabilization that could apply beyond physiological systems:

> *Might it not be useful to examine other forms of organization*
> *– industrial, domestic or social – in light of the organization of the body?*

His general question could be asked of environmental systems as well. In his text on *The Fundamentals of Ecology*, Odum (1971, 34) explains the term *homeostasis* is generally applied to the "tendency for biological systems to resist change and to remain in a state of equilibrium."

It's revealing to turn to Webster's dictionary for definitions. Webster's first entry is the narrow, physiological definition. Homeostasis is defined as the

> *tendency toward maintenance of a relatively stable internal environment in the bodies of higher animals through a series of interacting physiological processes.*

Webster's then lists an alternative definition which shows how broadly the term has come to be used. Homeostasis is also defined as the

> *tendency toward maintenance of relatively stable social conditions among groups with respect to various factors (such as food supply and population among animals) and to competing tendencies and powers within the body politic, to society, to culture among men.*

When thinking about environmental systems, we should take Cannon's concluding suggestion as a challenge to think about the interacting factors that allow the system to remain stable. His suggestion seems particularly relevant if we come across a system that has managed to survive over a long time period with large variations in the external factors. Cannon's views were predicated on the opportunity for evolutionary change:

> *The perfection of the process of holding a stable state in spite of extensive shifts of outer circumstances is not a special gift bestowed upon the highest organisms but is the consequence of a gradual evolution.*

Odum (1971, 35) stresses this point in his description of homeostasis of ecosystems. His text provides many examples to confirm that:

> *Really good homeostatic control comes only after a period of evolutionary adjustment. New ecosystems (such as a new type of agriculture) or new host-parasite assemblages tend to oscillate more violently and to be less able to resist outside perturbation as compared with mature systems in which the components have had a chance to make mutual adjustments to each other.*

Another general observation from physiology is that homeostasis of environmental systems will likely arise from a combination of negative feedback loops working in tandem. Once you begin to think in terms of feedback, it will be easy to spot one or two loops that govern system behavior. We should challenge ourselves to look beyond the first few loops that jump immediately to mind.

A final observation that will help in our study of environmental systems is to appreciate the extreme difficulty in verifying theories about homeostatic systems, especially if we focus our measurements on the central, controlled variable in the system. By design, homeostatic systems control the central variable to erase the impact of outside disturbances. Imagine, for example, that we wanted to verify the workings of the physiological mechanisms that maintain core temperature at 98.6 ºF degrees. We change the external conditions and take another temperature reading. What do we get?

98.6 ºF. In this situation, the body is almost too effective for our experiments to reveal the underlying mechanism, as explained by Riggs (1970, 398):

> *The truth is that in a normal unanesthetized human subject, feedback control of body temperature is so extremely effective that precise quantitative characterization of the mechanisms is well-nigh impossible.*

The temperature example raises questions of what should be measured. Certainly we measure the pivotal variable (i.e., body temperature). But equally important could be measurements of shivering and sweating, the actions that the body takes to maintain control. The nature of the threat to the body will be revealed by a combination of the controlled variable (temperature) and the extraordinary efforts (i.e., constant shivering) to maintain control.

Look for Positive as well as Negative Feedback

If Cannon's ideas are to prove useful in environmental systems, it is imperative than we expand our thinking beyond negative feedback. Our study of the environment must consider both positive and negative feedback. Cannon did not emphasize positive feedback, but the human body certainly relies on positive feedback to act in a useful manner (i.e., cell division and clot formation).

Although physiologists are certainly aware of positive feedback, it is negative feedback which dominates the discussion of homeostasis in social and economic systems. Richardson (1991, 48) observed that "to some in the social sciences, the feedback concept became identified, virtually synonymous, with homeostasis," and that the close association of feedback with homeostasis eliminated completely the consideration of positive feedback loops." The limited perspective of some social scientists should not limit your own thinking about the management of environmental systems. You'll need to consider both positive and negative feedbacks to build your understanding of environmental systems.

Stability and the Span of Control

Fig. 10.4 shows the images from the previous chapter on stability testing. The physiological discussion brings forth the image of the marble resting at the bottom of the cup. If disturbed from the normal position, the forces of gravity will negate the disturbance and bring the marble back to the normal position at the bottom of the cup. But this story only works if we limit the size of the disturbance. If we push the marble beyond the edges of the cup, the restorative forces are no longer operative. The marble is now beyond the span of control. Think of the span of control as the width of the cup.

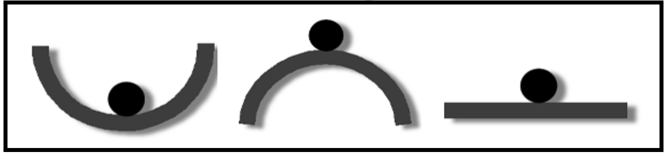

Fig. 10.4. Stable, unstable and neutral equilibrium.

The span of control is depicted in the pencil sketch in Fig. 10.5. The flat portion of the sketch resembles a plateau, so this portion of the sketch is sometimes called the *homeostatic plateau.* (The term homeostatic plateau is described by Hardin (1996, 159) and by Odum (1971, 34). I use the term *span of control* in this book.)

The vertical axis represents the equilibrium position of an internal variable which is subject to homeostatic forces. The horizontal axis represents an external input which can move either up or down. As long as the input remains within the span of control, the homeostatic processes maintain control. This portion of the diagram is marked with symbols for negative feedback to remind us that they are responsible for the control. And if you look closely, you'll see that the feedback symbols point in opposite directions. This is a visual reminder that the feedback process on the low side is probably very different than the feedback process on the high side.

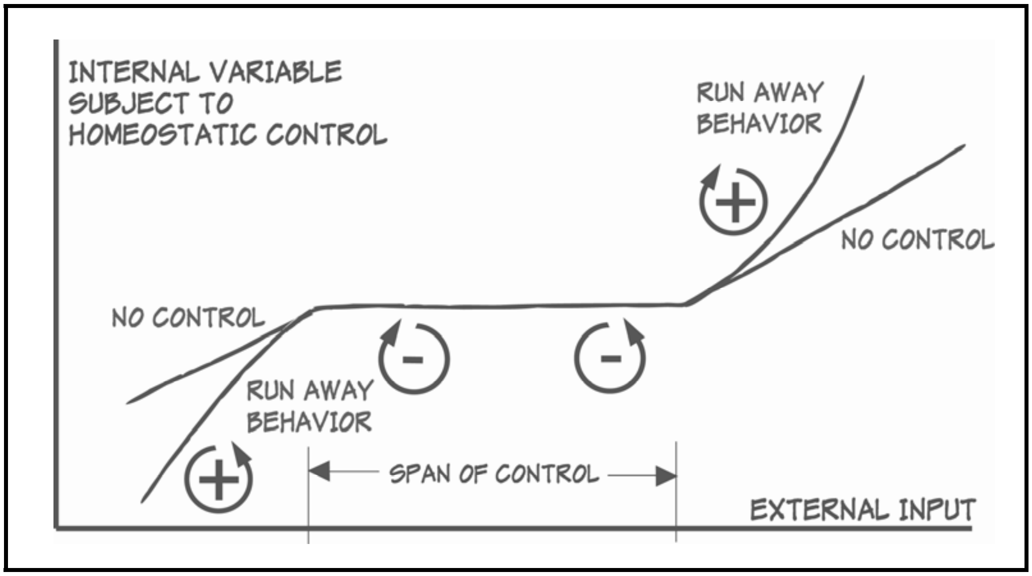

Fig. 10.5. The span of control.

Body temperature control provides a concrete example of the meaning of Fig. 10.5. The vertical axis would represent the body's core temperature, with a normal value around 98.6 ºF. This value is maintained in the face of cool ambient temperatures by a combination of mechanisms including shivering. It is maintained in the event of high temperatures by a different combination of mechanisms and sweating. The body is capable of "two-sided control," the general example depicted in Fig. 10.5 The body can maintain the core temperature near the normal value even with the ambient temperature as low as 63 ºF or as high as 90 ºF (Hardin 1996, 158). The span of control is from 63 to 90 ºF. Now, what happens if the ambient temperature lies outside the span of control? Hardin (1996, 158) describes this situation in detail. The body would experience runaway behavior caused by a vicious circle involving cell metabolism:

> *When the thermostat fails, runaway feedback takes over: higher temperature causes metabolic reactions to go faster which produces more body heat which raises the temperature which causes metabolic reactions to go faster… and so on. This runaway feedback (if not stopped) leads to death. Below the lower temperature limit, a similar runaway feedback leads to death from stoppage of metabolism.*

The body temperature is listed in Table 10.1 as the first of several examples of span of control. This is an example of two-sided control with runaway behavior expected if the ambient temperature is outside the span of control. The next entry is the home heating system in Fig. 9.3, an example of one-sided control. The home is equipped with a furnace, so it can deal with low outdoor temperatures. The indoor temperature can be maintained at the target value as long as the furnace is large enough to counteract the heat loss on a cold day. Let's imagine a home heating system with a target temperature of 65 ºF and a span of control from 0 to 65 ºF. Now suppose the outdoor temperature were to be -10 ºF. The indoor temperature would equilibrate at 10 ºF below the target. If the outdoor temperature were -20 ºF, the indoor temperature would equilibrate at 20 ºF below the target. We don't have control, but the situation is definitely different than the runaway behavior of the human body. I use the label "no control" in Fig. 10.5 to represent this situation.

Example (chapter)	External Factor (one sided or two sided)	Internal Variable (Y axis)	Outside the Span of Control
Body Temperature (BWeb)	ambient temperature (two sided)	core temperature	runaway behavior
Home Heating (ch 9; Fig. 9.3)	outdoor temperature (one sided)	temperature inside the house	no control
Blood Loss (ch 10)	size of the wound (one sided)	blood pressure	runaway behavior
Daisy World (ch 11)	solar insolation (two sided)	Daisy World planet temperature	no control
Salmon Population (ch 15)	our harvest fraction (one sided)	salmon returns to the Columbia	no control
Climate Change (ch 23)	our emissions of CO2 (one sided)	atmospheric CO2 and temperature	runaway behavior

Table 10.1. Examples of the span of control in this book.

Runaway behavior can occur when there are vicious circles waiting in the wings if the system is pushed too far. Runaway behavior is what Odum had in mind when describing ecological systems: "homeostatic mechanisms have limits beyond which unrestricted positive feedback leads to death." The blood loss example is an example. It is listed in Table 10.1 as a case of one sided control with the size of the wound as the external factor. The internal variable that must be controlled is blood pressure. The normal human body holds around 5 liters of blood and has developed extraordinary physiological responses that can limit the size of a wound and maintain blood pressure when there is a major loss of blood. Guyton & Hall (1996, 8) estimate that the natural processes can return the circulatory system to normal operation within two hours if the loss is less than 1 liter. But if the body is pushed beyond the span of control, runaway behavior is expected. If there is a loss of around 2 liters, a vicious circle will take over:

> *the amount of blood in the body is decreased to such a low level that not enough is available for the heart to pump effectively. As a result, the arterial pressure falls and the flow of blood to the heart muscle through the coronary vessels diminishes. This results in weakening of the heart, further diminished pumping, further decrease in coronary blood flow, and still more weakness of the heart; the cycle repeats itself again and again until death occurs.*

Once this vicious circle takes over, death is normally expected within a few hours.

Looking Ahead: Daisies, Salmon and Climate Change

The final three entries in Table 10.1 turn our attention to future chapters. The next chapter describes Daisyworld, a make-believe world invented to illustrate how the biota could interact with their physical environment to create a wide span of control. Chapter 15 describes a salmon population with thousands of salmon returning to the mouth of the Columbia every year. The external factor is the fraction of the returning salmon that are harvested. This population will show surprising resilience in the face of unusually large harvest fractions. The final entry is climate change. You'll read in chapter 23 that scientists fear that there are vicious circles waiting in the wings if the climate system is pushed too far. The threat of runaway behavior is one of the principal reasons why scientists and policy makers are calling for major reductions in emissions of CO2 to the atmosphere.

Further Readings

The BWeb lists system dynamics applications to physiology, and it provides modeling exercises on body temperature control.

Many biomedical problems (such as diabetes and hypertension) can be viewed as biological control problems, for which system dynamics is ideally suited (Gallaher 1996).

Hardin (1996, 159) describes homeostasis with examples of temperature control by different animals and humans. Fig 10.5 is my adaptation of Hardin's sketch of the homeostatic plateau.

Odum (1971, 34) describes homeostasis in ecological systems, and he draws on Hardin's description to depict the homeostatic plateau.

Richardson (1991) examines Cannon's ideas and their importance to the spread of feedback thinking within the social sciences and the systems sciences.

Capra (1996) describes the influence of Cannon's ideas in *The Web of Life,* a book for the general reader.