# CHAPTER 2

## CONTROL SYSTEMS AND HOMEOSTASIS

The title of this book is *The Nervous System in Action*. It is about action--things happening in the nervous system. It is appropriate to ask why things happen.

Sometimes we act in response to a specific stimulus. When an object approaches the cornea of the eye, the lid closes to protect the cornea from damage. When the tendon of a muscle is tapped, the muscle contracts. In these cases it is easy to identify the stimulus and the response. Other times it is not easy to identify what caused a particular action. Sometimes the actions are part of some continuous activity. The body regulates its temperature continuously. It may increase or decrease its temperature when it finds that it is too cold or too hot. In this case, temperature is being regulated by a **control system**, and the control is called **homeostasis**.

Control systems

Engineers refer to the first kind of action, a simple response to a stimulus, as an **open loop system**. It is useful to draw a diagram of how such a system works. Such a diagram is shown in Fig. 2-1. The system being controlled is contained within the box marked "controlled system." That might be the system that controls the eyelid, for example. There is an input to the system–the approaching object–and an output from the system–the closing of the lid. The system simply responds to the input.

On the other hand, the system that controls body temperature is called a **closed loop system**. The diagram for such a system is shown in Fig. 2-2. There are also a controlled system, input and output in this kind of system, but, in addition, there is something that senses the output of the system and effects some change in the input. It is this connection that makes this a "closed loop" system.

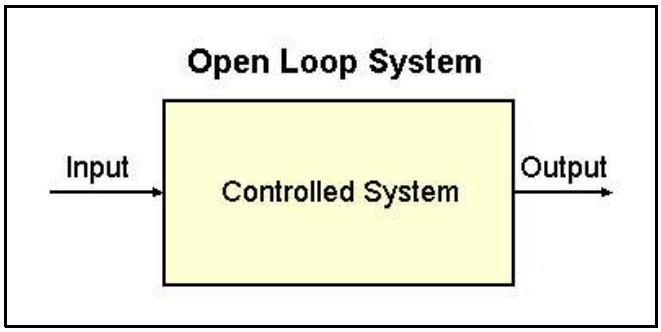


**Figure 2-1. An open loop system. The controlled system is indicated by the rectangle. Also indicated are the input to the system and its output.**

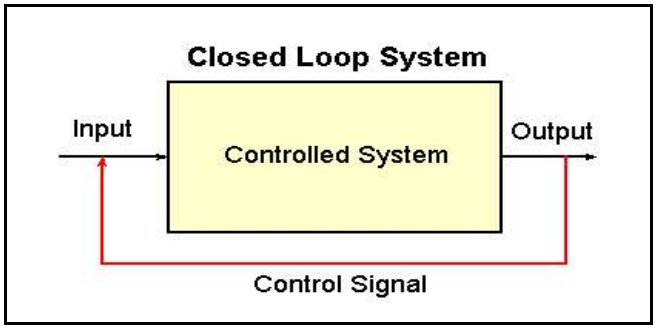


**Figure 2-2. A closed loop control system. The controlled system is indicated by the rectangle. Also indicated are the input, output and control signal.**

A diagram of the system that controls body temperature is shown in Fig. 2-3. Somewhere in the brain, perhaps the hypothalamus, the optimum temperature of the body (**set point**) is stored. That information is continuously available to some structure, we call the comparator. The comparator sends signals to

1. heat gain mechanisms in the preoptic area or anterior hypothalamus leading to
   - ✔ shivering
   - ✔ increased thyroid hormone output
   - ✔ increased activity in the sympathetic nervous system
   - ✔ piloerection
   - ✔ cutaneous vasoconstriction

2. heat loss mechanisms in the posterior hypothalamus leading to
   - ✔ decreased thyroid hormone output
   - ✔ sweating
   - ✔ cutaneous vasodilation

The output of these mechanisms will end as either a net increase or a net decrease in body temperature. The body temperature is sensed by thermal receptors (thermoceptors) in the brain and peripherally in the body, and the value is sent to the comparator where it is compared with the set point. If the value is less than the set point, then signals go mainly to the heat gain mechanisms; if it is greater than the set point, then they go mainly to the heat loss mechanisms. In this way, body temperature is constantly sensed and maintained constant (i.e., homeostasis).

Feedback control

In a **feedback control system**, the output is sensed and this information is used at an earlier point in the system--it feeds back. Actually, Fig. 2-4 illustrates feedback control.

Positive feedback systems. In a **positive feedback system**, the feedback is used to increase the size of the input. By nature, such systems are unstable, and they

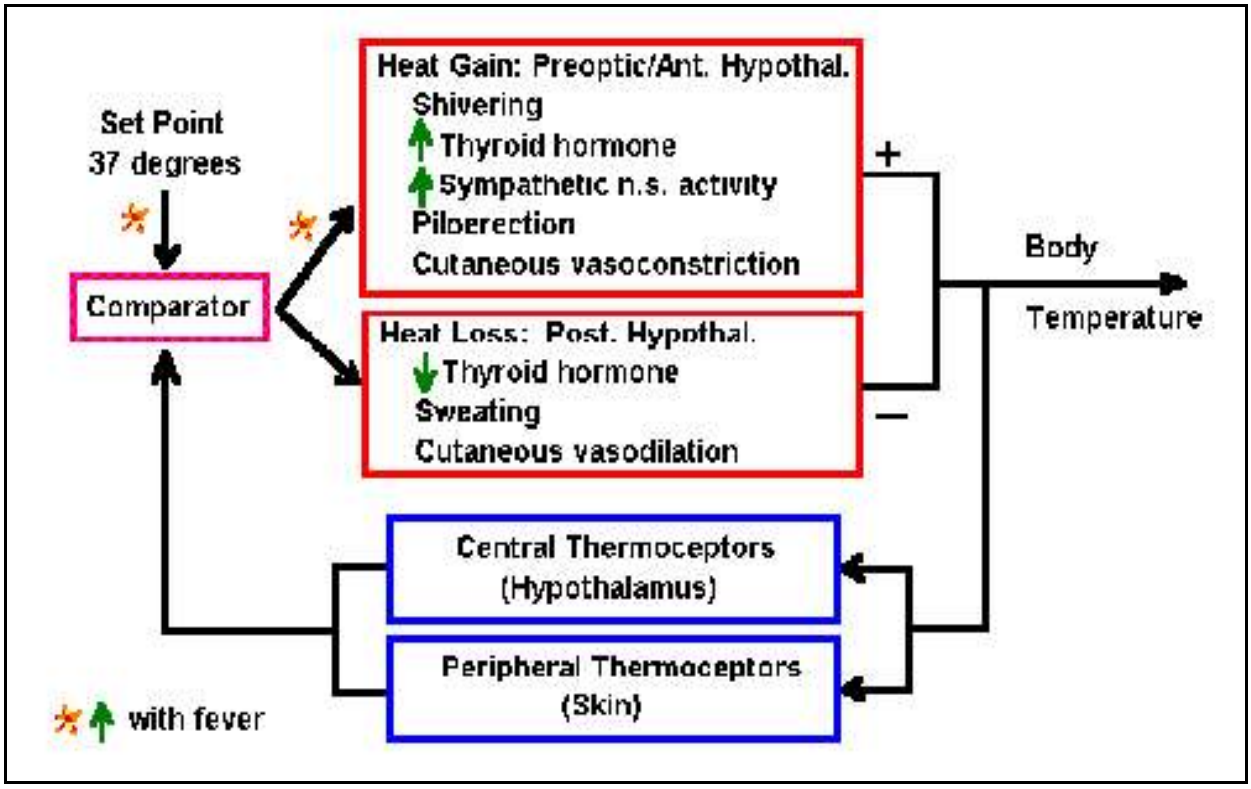


**Figure 2-3. Block diagram of the system for control of body temperature.**

are most often associated with pathological conditions. An example of a positive feedback system is shown in Fig. 2-4. In this diagram, hemorrhage leads to a decrease in blood pressure, which, it turn, leads to a decrease in flow in coronary arteries. The consequences of the decreased flow are

- ✔ increased lactic acid and hydrogen ion accumulation, which lead to further decrease in coronary blood flow
- ✔ increased vasodilator metabolites, which lead to further decreased blood pressure
- ✔ decreased contraction of the ventricles of the heart, which leads to decreased cardiac output and further decreased blood pressure

Clearly, none of these consequences is good. Several passages through this system will lead to excessive decrease in blood pressure and death. This is a positive feedback system because all of the consequences tend to increase the effect of the hemorrhage in lowering blood pressure.

Negative feedback system. In a **negative feedback system**, the feedback is used to decrease the size of the input. These systems are usually stable, and they are associated with beneficial regulation of physiological parameters. An example of a negative feedback system is shown in Fig. 2-5. In this diagram, hemorrhage leads to decreased blood pressure, which in turn leads to

- ✔ increased reabsorption of fluid
- ✔ increased constriction of blood vessels
- ✔ increased renal conservation of fluid

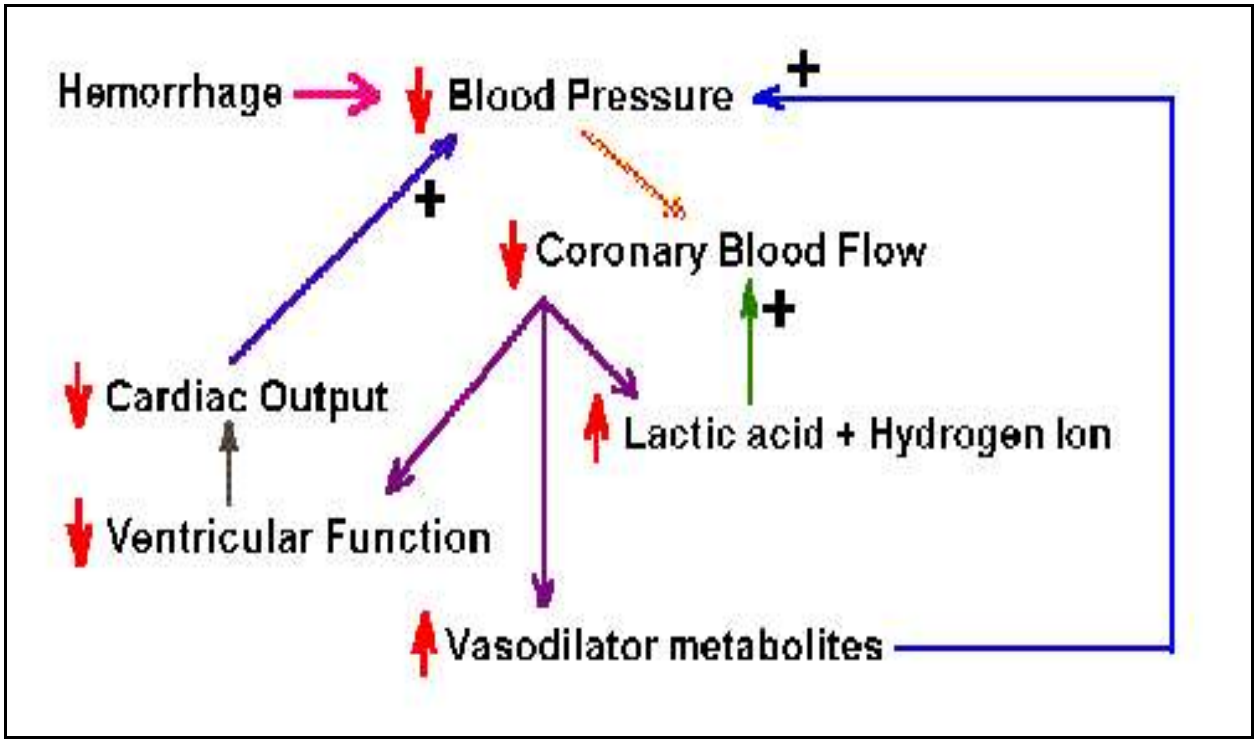


**Figure 2-4. Schematic diagram of the positive feedback system that is activated by hemorrhage. Like most positive feedback systems, this one is unstable, and if unchecked, will result in death.**

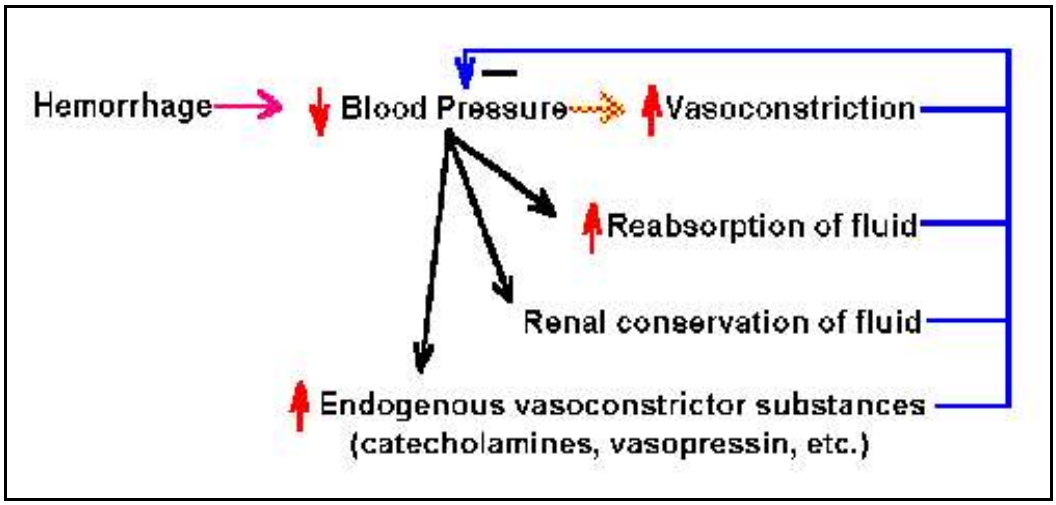


**Figure 2-5. Schematic diagram of the negative feedback system that is activated by hemorrhage.**

✔ increased endogenous vasocontrictor substances, such as catecholamines and vasopressin

All of these lead to increased blood pressure. This consequence counters the effect of the initial hemorrhage and is, therefore, beneficial. This is a negative feedback system because all of the consequences tend to decrease the effect of the hemorrhage in lowering blood pressure.

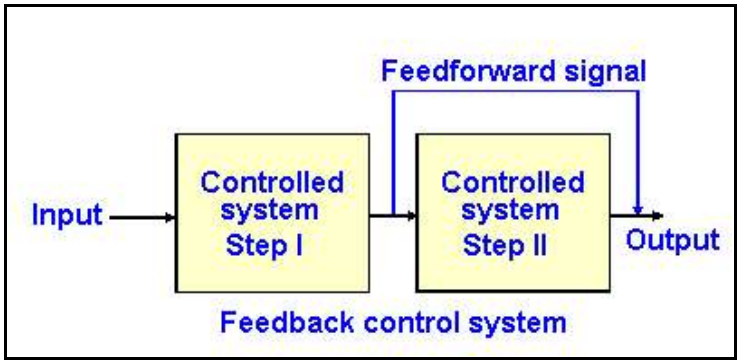


**Figure 2-6. Block diagram of a feedforward control system.**

Feedforward systems

In a feedforward system, the output of one stage of the processing of the control system is sent to a later stage of the process to affect later activity. The diagram for such a process is shown in Fig. 2-6. An example of a feedforward system is the preadaptation for exercise, changing the activity of postural muscles and of the vascular system in order to ready the body for the movement when it occurs. Moving the arm laterally shifts the center-of-gravity laterally, and the person would be in danger of falling over were not compensations made in the postural musculature to prepare for the movement.

Chronotropic control

The time-frame over which a parameter is controlled can be quite variable, ranging from seconds to years. Here are some examples of different ones.

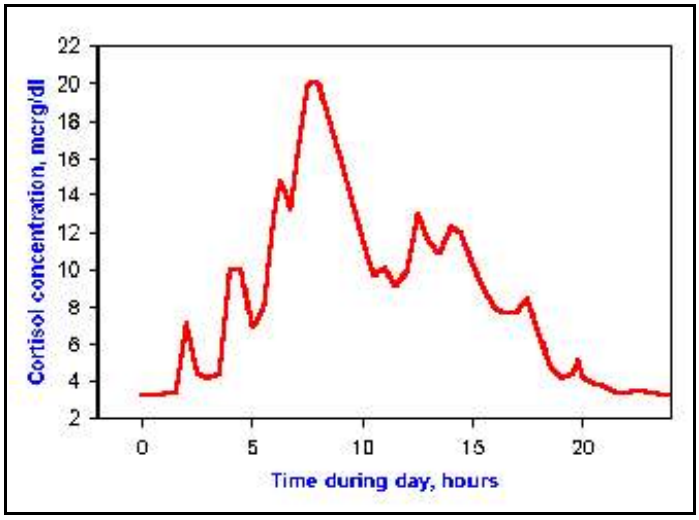


**Figure 2-7. Example of a diurnal rhythm. Cortisol concentrations in blood are controlled by a system that functions on a 24-hour cycle.**

Diurnal rhythms. Many parameters are regulated over a period approximating one day or 24 hours. They often are timed or "synched" by sleep-wakefulness or light-dark cycles. For example, the hormone cortisol, which is made by the adrenal gland and has important functions in metabolism of proteins, carbohydrates and fats, is controlled on a 24-hour cycle. Maximum concentration in blood are achieved between 7 and 8 am each day, with a nadir about midnight. This pattern can be seen in Fig. 2-7.

Lunar rhythms. Some parameters are regulated over a period approximating one month or 30 days. Some appear to be tied to phases of the moon, but for others the synchronizing event is unclear. The ovulatory cycle in the human female is an example of such a lunar rhythm. This is a complicated mechanism (4 of the hormonal participants are shown in Fig. 2-8), but it suffices for our purposes now to say that ovulation occurs in the middle of the cycle and is triggered by increases in luteinizing hormone (LH). This can be seen in the center of the lower graph of Fig. 2-8. The events depicted in the diagram are replayed every month during the reproductive span of the human female.

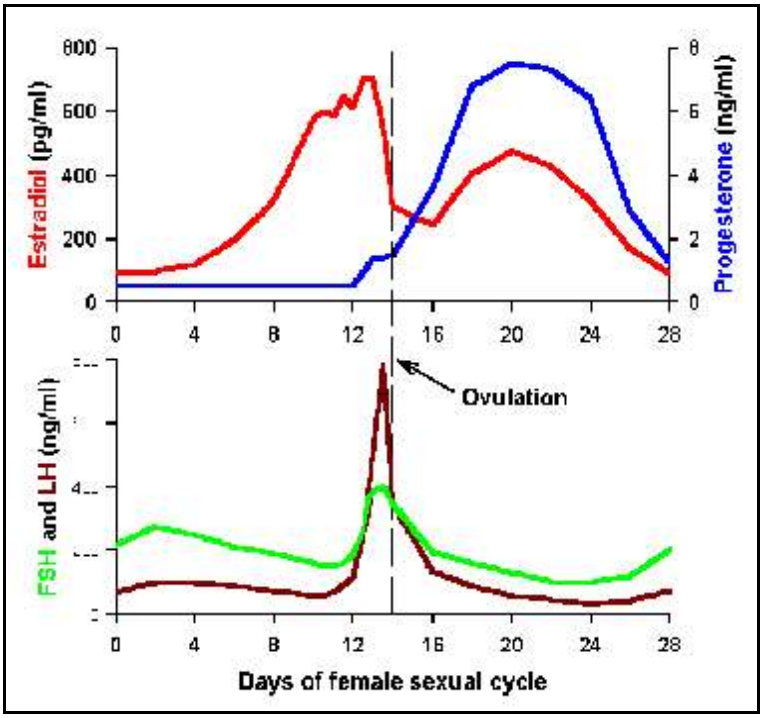


**Figure 2-8. Example of a lunar rhythm. Control of the ovulatory cycle in the human female occurs over an approximately 30-day period.**

Seasonal rhythms. Many events are regulated with a period approximating one year. These could be synchronized by changes in temperature, sunlight or tides, and often the triggering stimulus has not been identified with certainty. An example of such a seasonal rhythm is shown in Fig. 2-9. Here the brain weights (upper graph) and body weights (lower graph) have been measured on a monthly basis over a period of 4 years. Clearly, both

parameters are at a maximum in March through May and at minimums in January through February. These measurements were made in bank voles, which have definite annual breeding cycles. Perhaps they would not occur in humans, which lack such cycles, but undoubtedly some other parameters would have seasonal rhythms in humans.

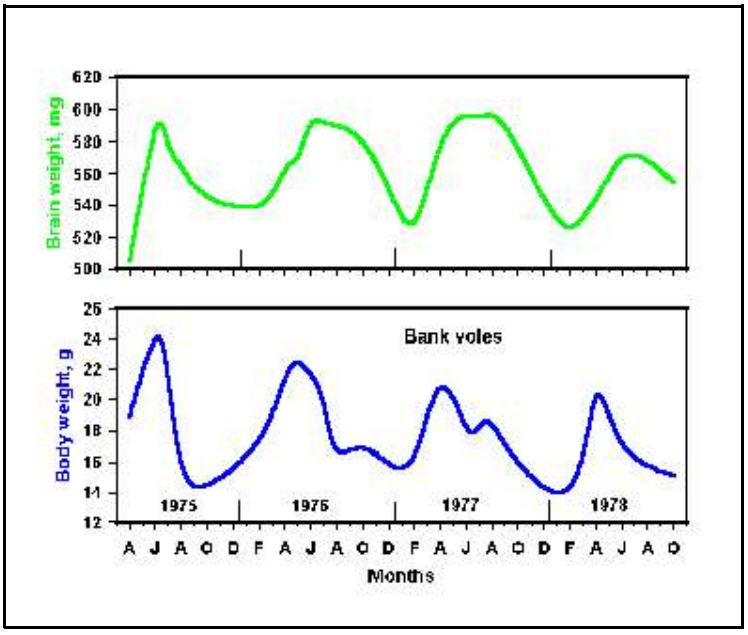


**Figure2-9. Brain (*upper*) and body (*lower*) weights in the bank vole are controlled with a period of about 1 year.**

Developmental rhythms. Some events are controlled on a life-time basis. For example, puberty occurs only once per individual. The same may be true for peak intellectual and physical performance. No one knows what triggers these events or why they occur when they do.

Continuous versus pulsatile control

In the nervous system, action potentials last between 0.25 and 1.0 msec. Slower nervous events last between 4 and 5 msec, sometimes longer. Synaptic transmission takes between 2.0 and 500 msec. None of these times approaches the scale of diurnal, lunar or seasonal rhythms. Obviously, if the nervous system were to control such rhythms, it would have to act repeatedly--just one action potential is unlikely to do the job.

The situation is slightly better for the endocrine system. The half-lives of a number of hormones are shown in Table 2-1. With the exception of thyroxine, none of these hormones has a half-life longer than a day. The release of luteinzing hormone (LH) is known to be pulsatile, each pulse lasting about 30 minutes.

Table 2-1

| Hormone | Half-life |
|---|---|
| Thyroxine | 6 days |
| Cortisol | 0.07 days |
| Testosterone | 0.04 days |
| Aldosterone | 0.016 days |
| Growth hormone | 0.017 days |
| Insulin | 0.006 days |

Some actions that must be controlled by the body are very brief, e.g., many movements. Some appear to be very long, e.g., growth. How can we get what appears to be continuous control with what must be a pulsatile controller? Let's take an example. Muscle contractions can last for part of a second, a minute or longer, but the controller, the action potential in the motoneuron does not last more than 2 msec. The answer lies in the time-constant, i.e., the duration of action, of the controlled system. In our example, the controlled system is the muscle. Muscle contraction is a mechanical event, which is triggered by the action potential, an electrical event. The mechanical event is very slow (requires 250 or more msec for a single response) compared to the electrical event. The effect of two action potentials lasts even longer. If several action potentials follow each other closely in time down the axon, then the contraction of the muscle will be continuous and maximal for that muscle. In this way, a pulsatile controller can produce seemingly continuous control.