Class Set

Do Not Mark

Homeostasis

Have you ever wondered why you don't faint every time you stand up? Does it surprise you that even if you skip lunch you still can walk and talk? Perhaps you never thought about these questions. Although it's obvious that you can stand up without fainting and continue to function without eating lunch, explanations for these occurrences really are quite complex. For instance, the cells in your brain all are exceedingly sensitive to tiny changes in the levels of oxygen and sugar in their immediate environment; even small decreases in these critical substances can cause fainting. One reason that the effects of gravity don't cause a drop in the blood and oxygen flow to the brain when you stand up is that your blood pressure immediately rises to maintain adequate oxygen flow. Likewise, you can get away with skipping lunch because a declining level of sugar in your blood stream triggers your liver to begin releasing the sugar it holds in storage.

Your body must continuously make these adjustments and many others to create and maintain an environment within which your brain can function. These adjustments are made *automatically*. Taken together, these complex internal adjustments assure that conditions within your body remain within rather narrowly defined limits, a condition of balance called **homeostasis** (see Figure E5.1).

Humans are not the only organisms that maintain homeostasis. In fact homeostasis is a fundamental characteristic of *all* living systems. In many animals internal organs that are similar in function to those in humans help to maintain homeostasis. In plants, specialized structures, such as those illustrated in Figure E5.2, have evolved that enable plants to maintain balanced conditions.

In simpler organisms, however, much simpler mechanisms operate to maintain homeostasis. In a single-celled organism such as an amoeba, the removal of toxic waste products is accomplished without complicated internal organs and with very few specialized structures. Instead, basic processes, such as diffusion and osmosis, are sufficient. Even though these mechanisms for maintaining homeostasis may seem simple when compared with an entire circulatory system, they are critical for maintaining the amoeba's life. Ultimately different organisms must balance different conditions and may use different mechanisms to do so. For all organisms, however, maintaining the delicate homeostatic balance means life, and losing this homeostatic balance for an extended period of time means death.

In order to maintain homeostasis, two things are required: an organism must be able to *sense* when changes have occurred in the external and internal environment, and it must be able to *respond* with appropriate adjustments. For example, humans can monitor **stimuli** or external signals such as cold because we have sensory neurons in our skin that allow us to feel the outside temperature. Once the message "cold" is received in the brain, our body can respond by changing blood flow. This change is involuntary, or *automatic*, because we do not consciously control the physiological processes that cause the heart rate to increase or decrease or the blood vessels to dilate or constrict. In other words, we do not have to *decide* that the body should attempt to keep the brain, heart, and liver at a nearly constant temperature even if that means sacrificing tissues at the surface of the body; the body will attempt to keep the core warm anyway.

The human body's response to change is quite specific as well as involuntary. For example, the body responds to cold temperature by diverting circulation to keep the most important internal organs warm. This type of response is appropriate for the external conditions. If the body becomes too hot, however, the circulatory system diverts blood flow away from the internal organs to protect them from damage caused by excess heat.

Even though these examples are rather dramatic, the human body routinely senses and responds to thousands of small changes each day, most of which you are not even aware. It is through many small, specific, and automatic changes that living organisms are able to sense and react to an environment that is ever-changing and sometimes hostile. Luckily, the mechanisms responsible for maintaining balance are always on the job.

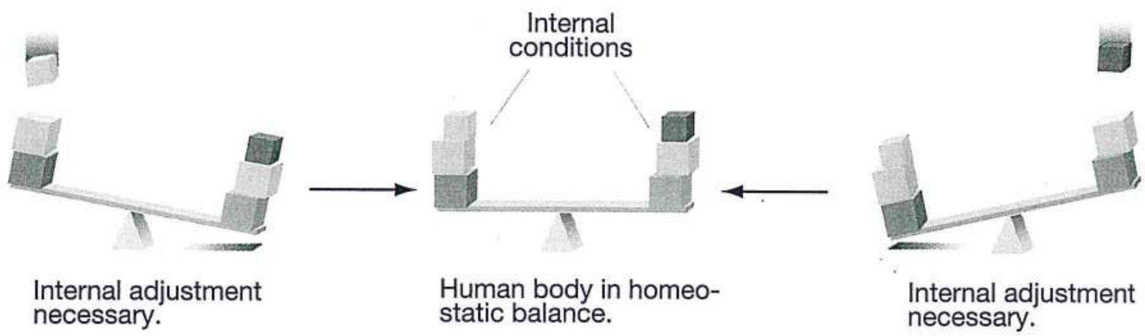


Figure E5.1 Homeostasis The human body is maintained in a state in which the internal conditions are balanced. When the balance is disturbed, the body adjusts its internal conditions to restore balance.

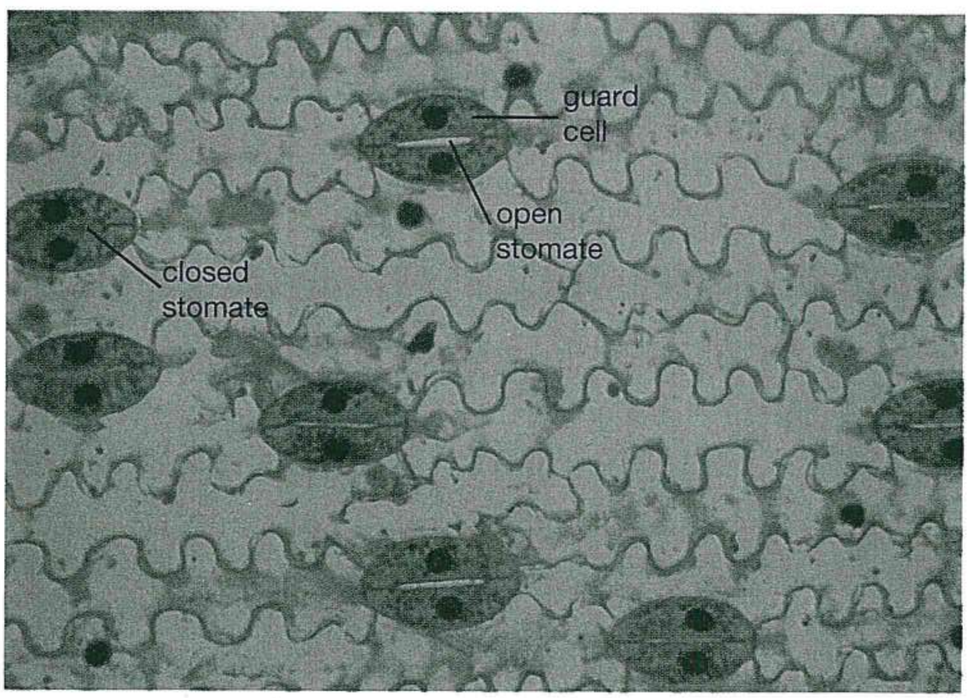


Figure E5.2 Guard cells control the rate of water loss in plants. Water loss is controlled by the condition of special cells, called guard cells, that regulate the size of microscopic pores in leaves. These pores are called **stomates**. When the plant has sufficient water, the guard cells swell and the stomates open. Water then evaporates through the stomates. When the plant is low on water, the guard cells shrink, and the stomates remain closed, which preserves water. Based on the appearance of stomates in this leaf, how would you describe this plant's water balance?

Careful Coordination

As you learned in Chapter 4, multicellular organisms face a great challenge in maintaining internal conditions. Most of their cells are buried deep inside their bodies, far removed from the external environment from which they must obtain their oxygen and nutrients. They, therefore, are not able to rely on simple processes to maintain balance. In humans, acceptable internal conditions are created through the interactions of a number of organ systems. These interactions allow cells deep in the body to maintain contact with the outside, even though this contact may be indirect. Organ systems contain many organs that communicate with each other. Continuous, coordinated adjustments made by all of the body's organs help to *regulate* homeostatic balance.

Continuous automatic adjustments are possible because most body systems are directed by the nervous system and the endocrine system—two organ systems that reach every part of the human body. The nervous system is known for directing rapid, short-term, and very specific responses in the body. A reflex, such as the fortuitous jerk that pulls your hand back when you accidentally touch something hot, is an example of a rapid nervous system response. This reflex is a homeostatic response to a potentially dangerous rise in skin temperature, and it illustrates the interaction of sensory, nerve, and muscle systems. In this case, receptors in the skin send nerve signals to nerve cells in the spinal cord. These in turn stimulate muscles in the arm to contract suddenly, and the hand withdraws from the hot surface.

In contrast, the endocrine system, which is illustrated in Figure E5.3, usually directs slower and longer-lasting changes. In cases of dehydration, for instance, sensors in a specialized part of the brain called the hypothalamus (Figure E5.4a) detect a shortage of water in the body. These sensors in turn respond by signaling the pituitary, an endocrine gland also located in the brain, to release chemical messengers called **hormones** into the blood stream (Figure E5.4). Hormones trigger changes in the activities of a wide variety of cells and organs throughout the body. (See the table *Origins and Effects of Hormones*, Figure E5.5, on pages E63-E64 for more information about the endocrine system.) At this point, the endocrine system interacts with the circulatory system because the blood stream carries the hormone vasopressin to the kidneys. The kidneys, which are part of the urinary system, respond to this signal by retaining more water. The net effect of all this sensing, responding, and interacting is a regulated decrease in urine output and an increase in the desire to drink water, as illustrated in Figure E5.6. The general process by which the body automatically senses changing conditions and responds to them is called **feedback**.

Feedback plays a significant role in homeostasis because it is the mechanism that regulates how the body responds to changing conditions when an imbalance is detected. Feedback can operate in one of two ways. It can direct organ systems to interact in ways that change internal conditions *away from* the initial conditions or *toward* the initial conditions. The regulation of blood pressure, that is the pressure exerted by blood against the walls of circulatory vessels, serves as a good example of changing conditions away from initial conditions. Like many other internal conditions, blood pressure must be maintained within very defined limits. If the pressure becomes too low, nervous system sensors called baroreceptors, located on large arteries in the chest and neck, send a signal through the nervous system to the brain. As

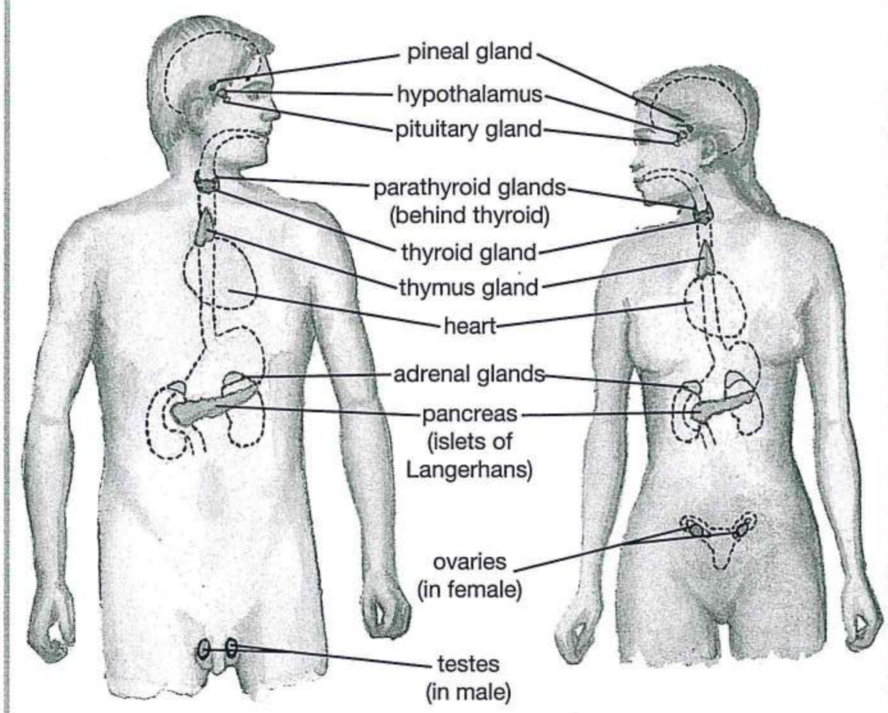


Figure E5.3 The endocrine system The dotted lines show non-endocrine organs, such as the stomach and kidneys.

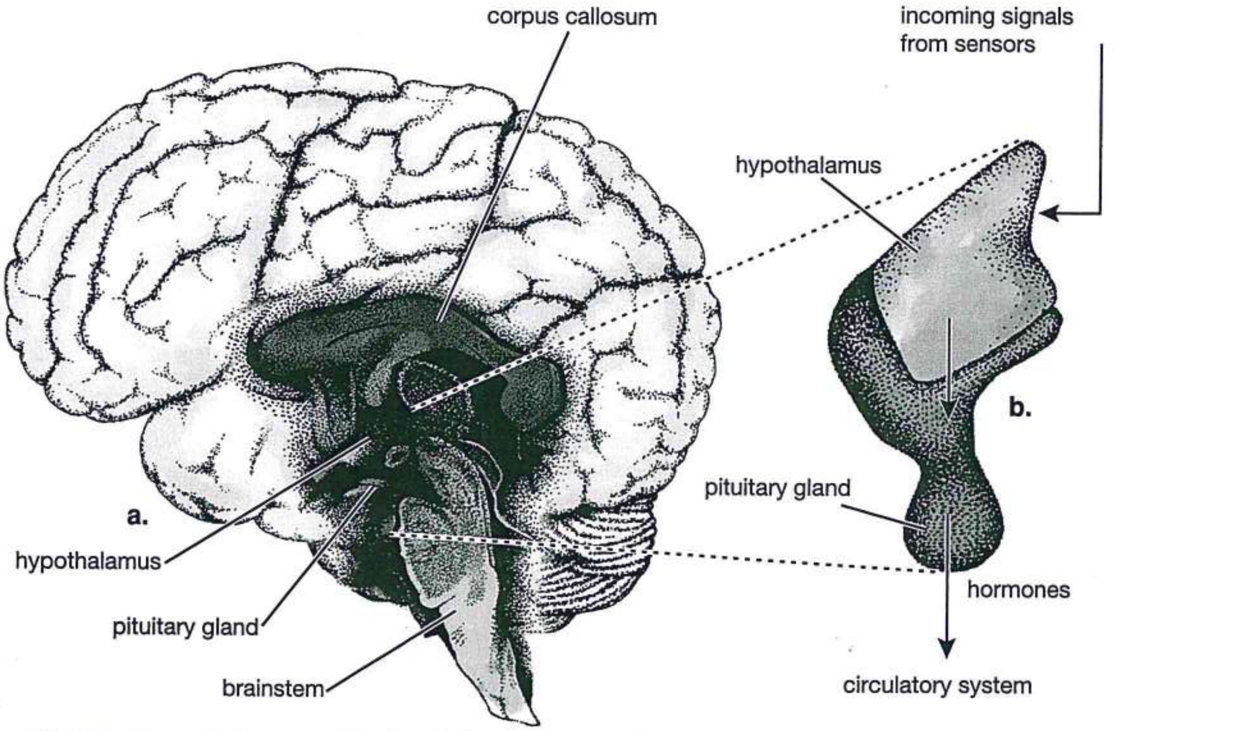


Figure E5.4 The hypothalamus a. The hypothalamus is a specialized part of the brain that is part of both the endocrine system and the nervous system and is involved in detecting changes in internal conditions. b. The hypothalamus responds to feedback by signaling other endocrine organs. In response to dehydration, the hypothalamus can release hormones that act on the pituitary gland, which lies just underneath the hypothalamus in the brain. The pituitary gland then releases hormones into the circulatory system.

Gland/Organ	Hormone	Target	Principal Action
Pineal	melatonin	unknown in humans—perhaps hypothalamus and pituitary	regulates circadian rhythms (day/night cycles)
Hypothalamus	corticotropin-releasing (CRH)	anterior pituitary	stimulates secretion of ACTH
	gonadotropin-releasing hormone (GnRH)	anterior pituitary	stimulates secretion of FSH and LH
	prolactin-inhibiting hormone (PIH)	anterior pituitary	inhibits prolactin secretion
	somatostatin	anterior pituitary	inhibits secretion of growth hormone
	thyrotrophin-releasing hormone (TRH)	anterior pituitary	stimulates secretion of TSH
Hypothalamus (via posterior lobe of pituitary)	antidiuretic hormone (ADH or vasopressin)	kidney	controls water excretion
	oxytocin	breasts, uterus	stimulates release of milk; contraction of smooth muscle in childbirth

Figure E5.5 Origins and Effects of Hormones

Figure E5.5 Origins and Effects of Hormones (Continued)

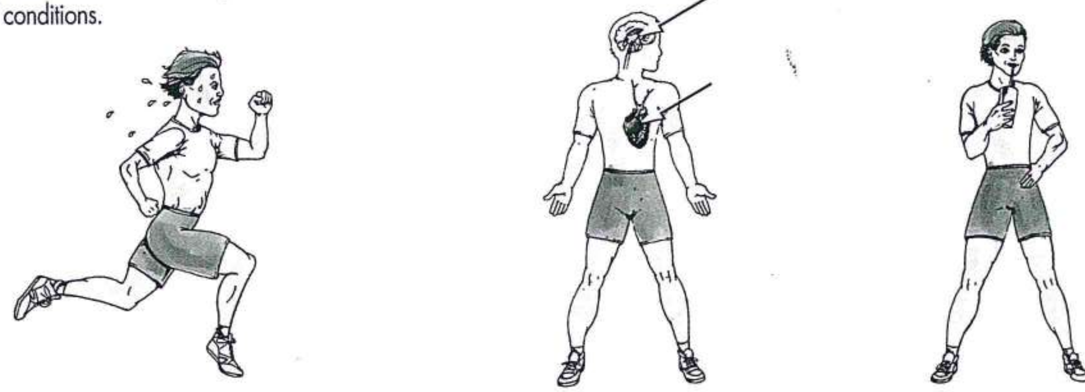
Gland/Organ	Hormone	Target	Principal Action
Pituitary (anterior lobe)	adrenocorticotropic hormone (ACTH)	adrenal cortex	secretes steroid hormones
	follicle stimulating hormone (FSH)	ovarian follicles, testes	stimulates follicle; estrogen production; spermato-genesis
	growth hormone (GH)	general	stimulates bone and muscle growth, amino acid trans-port, and breakdown of fatty acids
	luteinizing hormone (LH)	mature ovarian follicle, interstitial cells of testes	stimulates ovulation in females, sperm and testos-terone production in males
	prolactin	breasts	stimulates milk production and secretion
	thyroid stimulating hormone (TSH)	thyroid	secretes thyroxine
Parathyroid	parathyroid hormone (parathormone)	intestine, bone	stimulates release of cal-cium from bone; decreases excretion of calcium by kidney and increases ab-sorption by intestine
Thyroid	calcitonin	intestine, kidney, bone	inhibits release of calcium from bone; decreases ex-cretion of calcium by kidney and increases absorption by intestine
	thyroxine	general	stimulates and maintains metabolic activities
Thymus	thymosin	lymphatic system	possibly stimulates develop-ment of lymphatic system
Heart	atrial natriuretic factor (ANF)	blood vessels, kidneys, adrenal glands, reg-ulatory areas of the brain	regulates blood pressure and volume; excretion of water, sodium, and potas-sium by the kidneys
Adrenal cortex (outer portion)	aldosterone	kidneys	affects water and salt balance
	androgen, estrogen	testes, ovaries	supplements action of sex hormones
	cortisol	general	increases glucose, protein, and fat metabolism; reduces inflammation; combats stress
Adrenal medulla (inner portion)	epinephrine norepinephrine	general (many regions and organs)	increases heart rate and blood pressure, activates fight-or-flight response
Pancreas (endocrine tissues)	glucagon	liver	stimulates breakdown of glycogen to glucose
	insulin	muscle, liver cells	lowers blood sugar level; in-creases storage of glycogen
Reproductive organs			
Ovaries	estrogen	general	stimulates development of secondary sex characteris-tics; bone growth; sex drive
	progesterone	uterus (lining)	maintains uterus during pregnancy
Testes	testosterone	general	stimulates development of secondary sex characteris-tics; bone growth; sex drive

Figure E5.7a shows, the brain then responds by sending a signal to speed the heart rate, which in turn increases the blood pressure. In addition, the brain also signals small arteries and veins to constrict, or narrow, thus further increasing blood pressure. In this case, the initial condition was low blood pressure and the response was to change conditions to increase the blood pressure. Such changing conditions represents a type of feedback known as **negative feedback**.

Figure E5.7b shows an example of **positive feedback**, which is a type of regulation in which the body responds to changes by adjusting internal conditions toward the initial condition. In the example shown, the initial condition is a small clot that begins to develop in response to a bleeding wound. Positive feedback triggers a regulatory response in which still more clotting fibers accumulate at the site of injury. This has the effect of increasing the size of the clot, which helps to reduce the loss of blood.

By delicately balancing positive and negative feedback mechanisms, the body is able to regulate all of the changing internal conditions that humans typically experience. Indeed, the process of regulating blood pressure in the brain is so finely tuned that even when the body's blood pressure is slightly high, such as when you exercise, the blood pressure in the brain remains normal. This is because instantaneous adjustments are made to maintain normal pressures as well as the necessary amount of blood flow that is so important to the brain.

Figure E5.6 Feedback and regulation work to reverse the effects of dehydration and restore balanced internal conditions.



1. **Change in internal condition.** During exercise, water is lost through heavy breathing. This can lead to dehydration.
2. **Feedback from sensors.** Sensors in the hypothalamus and near the heart detect a loss of water. The concentration of certain components in the blood is an important signal.
3. **Regulation.** Hormones such as vasopressin are released into the circulatory system in response to the feedback signals. Vasopressin acts on the kidneys, causing them to retain water. You also feel thirsty.

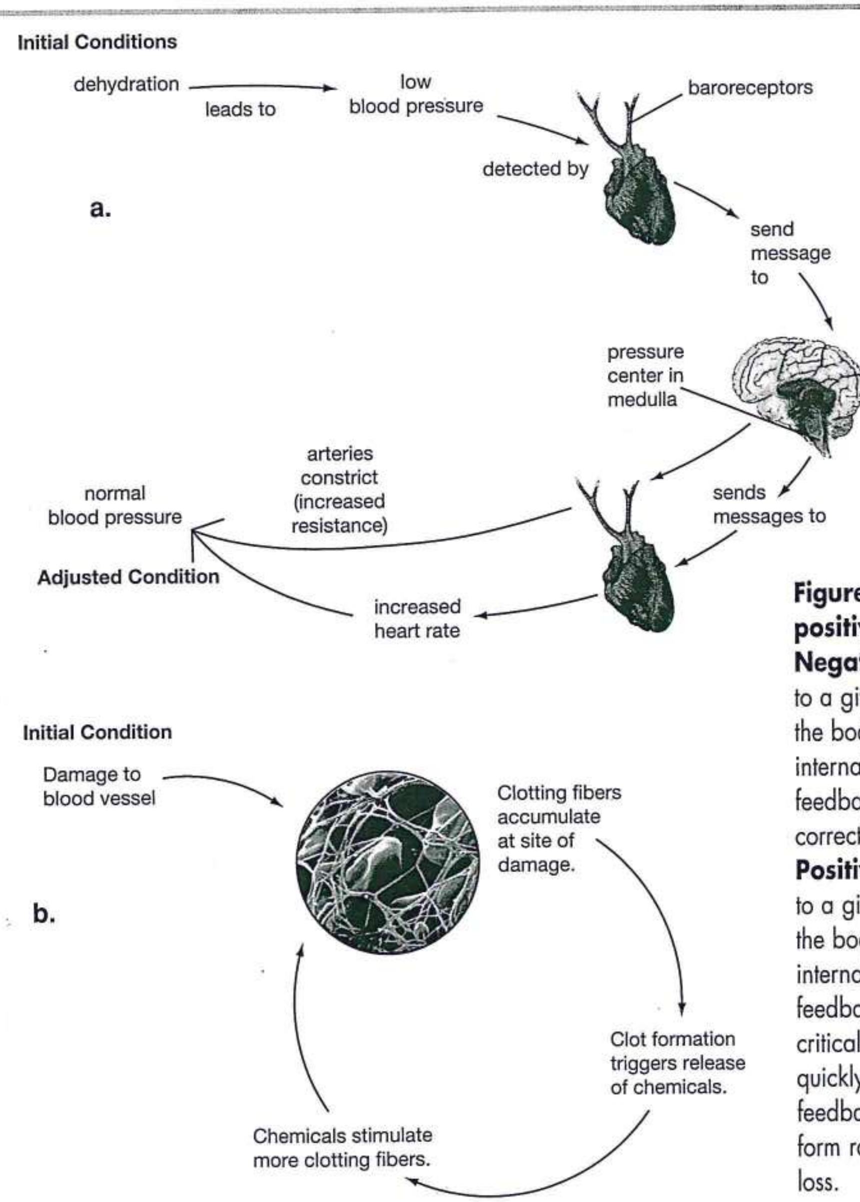


Figure E5.7 Negative and positive feedback a. **Negative feedback** In response to a given set of initial conditions, the body responds by adjusting internal conditions. Negative feedback triggers changes that correct an abnormal situation. b. **Positive feedback** In response to a given set of initial conditions, the body responds by adjusting internal conditions. Positive feedback occurs when some critical process must be completed quickly. In this case, positive feedback assures that a clot will form rapidly to minimize blood loss.

Regulation and Homeostasis

by Knut Schmidt-Nielsen

Source: From *Developing Biological Literacy: A Guide to Developing Secondary and Post-secondary Biology Curricula* by BSCS.

Living organisms tend to maintain a relatively constant state that is optimal for survival. This constancy is well regulated and is called homeostasis. Deviations from the usual state or composition of the organism are met with corrective action. Deviations that are too great cause serious difficulties and eventually death. Homeostasis is important at all levels, from the single cell through the level of organs to the entire organism. In ecology the term applies to the self-regulating maintenance of population densities.

Living organisms have elaborate mechanisms to resist changes and maintain constant conditions. Regulatory mechanisms respond to deviations or departures from the normal; corrective action returns the system to the normal range. Mechanisms to maintain constancy involve **feedback** control. A familiar example of feedback control is the heating system of a house that is regulated by a thermostat. If the temperature falls below the desired temperature (the setpoint), it serves as a signal that causes corrective action (more heat), thus restoring the system to the desired temperature. When the deviation (in our example a decreased temperature) is offset by a corrective action in the opposite direction (increasing the temperature), it is called **negative feedback**.

A biological example of feedback control is the maintenance of a relatively constant body temperature. If our body temperature increases, we normally increase heat loss by sweating; if the body temperature drops, we respond by shivering to increase heat production. The responses thus tend to maintain the body temperature at the normal level.

An example of homeostasis in physiology is the aquatic animals that maintain salt concentrations in their bodies different from those in the surrounding water. Marine invertebrates maintain the same total osmotic concentration as in the surrounding seawater, but the concentrations of various salts in their blood invariably differ from those in the surrounding water. Similarly, the concentrations of various salts inside the cells differ from those in the blood and extracellular body fluids. These differences are characteristic of each animal species, and their lives depend on the maintenance of these differences. Marine fish, in addition to maintaining internal concentrations different from those in seawater, maintain their overall osmotic concentration at about one third of that in seawater.

Freshwater has very low concentrations of salts, and both invertebrates and vertebrates that live in fresh water (fish, some amphibians, and reptiles) maintain internal concentrations that far exceed those in the very dilute water. The maintenance of differences between the organism and the surrounding water depends on elaborate control mechanisms, a subject that generally is referred to as osmoregulation.

Many of the processes that serve to maintain constant conditions in higher vertebrates, and especially in mammals, are reasonably well known and understood. Such functions include the maintenance of constant body temperature, constant heart and breathing rates, constant blood pressure, and constant level of blood sugar. For example, the mechanisms involved in the maintenance of a constant water content of the body, in spite of changes in water intake, are well known. If water intake is restricted, the kidneys respond by reducing the volume of urine, eliminating waste products in high concentrations with a minimal use of water. If water intake is large, the kidneys respond by producing large volumes of dilute urine. These changes in renal function are under hormonal control; if there is water shortage, the pituitary gland produces antidiuretic hormone ADH (also known as vasopressin); if there is a surplus of water to be eliminated, the production of the hormone ceases and the urine volume increases. In mammals it is the retention and conservation of water that is promoted by the antidiuretic hormone ADH. In other animals it may be water elimination that is augmented by a hormone. Consider a mosquito, which in a single blood meal may ingest twice its body weight, a load that greatly impairs its flying and maneuvering ability unless it is rapidly eliminated. A blood-sucking mosquito, before it has even completed its meal, begins to urinate at a high rate. The sudden increase in urine production is regulated by a diuretic hormone that stimulates secretion of fluid by the Malpighian tubules.

We are familiar with the responses to acute changes in physiological demands such as exercise. The increased oxygen demand during exercise is met by increased rate and depth of breathing, increased blood flow to the working muscles, and increased heart rate (plus a moderate increase in stroke volume). These changes are carefully regulated to meet the demands and, when exercise ceases, the rates return to the resting levels.

Also familiar to us are the slow changes that occur in response to increased physical demands on the organism during athletic training. The changes involve well-controlled reorganization and remodeling of physiological systems in response to the increased demands. Muscles subjected to increased use respond with growth and with less obvious changes, such as increases in number of mitochondria, in Krebs cycle enzymes, and in cytochromes—responses that augment the performance of the muscles. Training also augments the heart's capacity for pumping blood and the lungs' capacity for oxygen uptake.

If the bones are subjected to long-term changes in forces exerted on them, they undergo well understood changes. Bones are far from dead and inactive mineral tissue; living cells in the bones (osteoclasts and osteoblasts) respond to changes in the forces exerted on the bones by resorption and deposition of mineral substances (crystals of inorganic calcium phosphates). A major question that today we are unable to answer fully is how the forces on the bones are communicated to the cells responsible for the remodeling of the bones.

The immediately preceding sentence points to an unsolved problem that is of the greatest importance. Although the mechanisms involved in the maintenance of steady state responses to short-term changes such as exercise are reasonably well understood, the mechanisms involved in the regulation of long-term changes are not. For example, consider the ability of the liver to regenerate. A mammal can tolerate surgical removal of a large portion of its liver. The remaining liver will begin to regenerate the lost tissue. The growth of new tissue continues until the liver reaches its initial size, and then it ceases. Little is known about the signals that initiate the regeneration except that certain growth-promoting substances are involved, and nothing is known about the signals that make the growth cease when the regenerating liver reaches the "correct" size.

Many related problems pertain to other areas of the growth and development of an organism. We know, for example, that the normal growth of a human infant depends on the release of pituitary growth hormone. The sudden spurt in growth of the human male in early puberty is initiated by the influence of gonadal hormones and their effect on the production of growth hormone, but what in turn regulates this increase in production of male hormone and makes it cease when the body has reached the "correct" size is poorly understood.

Consider a fertilized mammalian egg (refer to Figure E5.8) that has undergone two divisions and hence has reached the four-cell stage. One of the four cells can be removed and then transplanted into the uterus of a suitably prepared female of the same species. This cell, only one fourth of the size of the original egg, is now capable of growing into a normal embryo that eventually develops into a normal, full-sized fetus that is delivered at term. We do not understand how a single cell that represents only a fraction of the mass of the fertilized egg grows into a normal fetus, what signals control its growth to the right size, and what makes growth cease at the exact correct size. How does the organism "know" what its right size is?

Today, we are seeking answers to these and similar questions pertaining to the long-term control of growth and development, as well as long-term remodeling in response to changing demands on the organism. Our current knowledge is inadequate, and the many unsolved problems in these areas are foremost in the minds of many contemporary biologists.

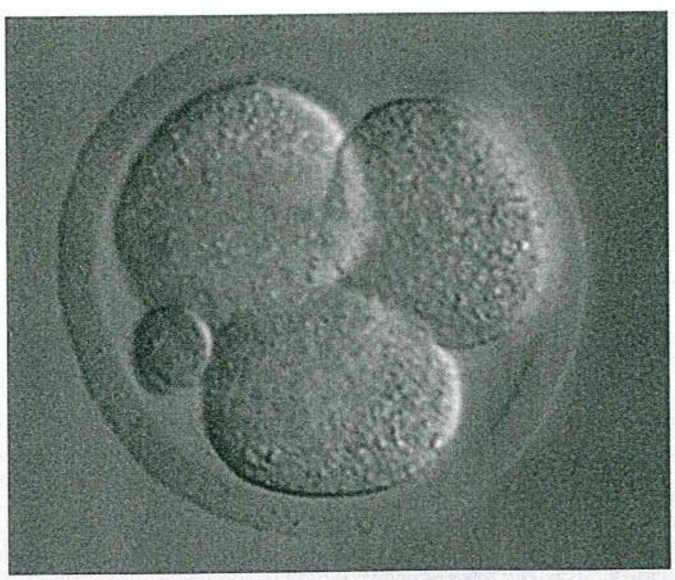


Figure E5.8 Mouse embryo at four-cell stage of development Each of the large mouse cells (only three are visible) will develop into a normal mouse if separated from each other. How does the mouse embryo "know" the right size of a mouse?