4

A Biological Perspective on Purpose: The Physiology of Bernard and Cannon

We must therefore seek the true foundation of animal physics and chemistry in the physical-chemical properties of the inner environment. The life of an organism is simply the result of all its innermost workings. All of the vital mechanisms, however varied they may be, have always but one goal, to maintain the uniformity of the conditions of life in the internal environment.
—Claude Bernard (1878; quoted in Rahn 1979, p. 179).

Claude Bernard and the Internal Environment

The seven years from 1859 to 1865 are noteworthy for several revolutionary advances that took place in the life sciences. In 1859 Charles Darwin published *The Origin of Species* in which he convincingly argued for a common ancestor to all living organisms on earth and explained the great diversity of their forms as resulting from evolution by natural selection (the application of Darwin's insight to understanding behavior will be taken up in the next two chapters). From 1860 to 1865, French chemist Louis Pasteur (1822–1895) conducted a series of experiments that laid to rest the theory of spontaneous generation of life (showing, for example, that yeast and bacteria would not grow in decaying matter that had been sterilized and protected from exposure to air and dust) and laid the foundation for modern medicine with his germ theory of disease. In 1865 Austrian monk and pea gardener Gregor Mendel (1822–1884) discovered certain regularities of heredity that eventually led to the development of the fields of genetics and molecular biology. And also in 1865, Claude Bernard published his now classic *Introduction à l'étude de la medicine experimentale* (English translation 1927).

The contributions of Darwin, Pasteur, and Mendel are well known even among nonscientists. Bernard's name is much less familiar despite his numerous important contributions to our understanding of internal systems and their functioning, or physiology, of living organisms. Bernard's contributions include the following (Fruton 1975, p. 35):

1 The discovery of the role of the pancreatic secretion in the digestion of fats (1848)
2 The discovery of a new function of the liver—the "internal secretion" of glucose into the blood (1848)
3 Induction of diabetes by puncturing the floor of the fourth ventricle [of the brain] (1849)
4 The discovery of the elevation of local skin temperature on section of the cervical sympathetic nerve (1851)
5 Production of sugar by washed excised liver (1855) and the isolation of glycogen (1857)
6 The demonstration that curare specifically blocks motor nerve endings (1856)
7 The demonstration that carbon monoxide blocks the respiration of erythrocytes (1857)

It could be held, however, that Bernard's most important contribution to our understanding of the phenomenon of life is not included among any of these discoveries. Through his exhaustive research on internal systems of living organisms, Bernard came to understand that the function of physiological processes was to *regulate* or *control* the internal environment (*milieu intérieur*) of the organism. And he understood that this control, so essential to life, was achieved by normal laws of chemistry and physics, not by any special vitalist entities or processes.

As an example of control of the internal environment, let us consider the topic of the doctoral dissertation Bernard submitted in 1853. The countless living cells in a mammal's body require a continuous supply of food that must be present at all times in blood as glucose. If too little glucose is present, a condition known as hypoglycemia, the body's tissues will starve and, most important, the brain will no longer be able to function, leading to loss of consciousness and ultimately death. A very high concentration of glucose in blood, or hyperglycemia, is also dangerous since it may result in loss of consciousness and death, and less extreme hyperglycemia can cause thickening of capillaries and circulatory disease. So in healthy humans the level of blood sugar is maintained within quite narrow limits to 90 milligrams per 10 deciliters of blood. This control is maintained even if we go for many hours and even days without eating or if we instead stuff ourselves beyond reason over a few hours at a restaurant or holiday family meal.

How is this precise control of blood sugar level maintained? Bernard correctly identified the liver as a reservoir for glucose (where it is actually stored in a modified form known as glycogen), releasing it into the blood as necessary by the body's cells. He believed that the central nervous system played a direct role in the control of glucose levels, but we know today that the control center is located in the pancreas in clusters of cells called pancreatic islets or islets of Langerhans. Within these clusters are two types of cells, alpha and beta cells. Both have chemical sensors that are sensitive to the amount of glucose in the blood, but each has a different concern. Alpha cells become active when they detect blood glucose levels below 90 ml/10 dl and respond by producing glucagon, an enzyme whose principal effect is to stimulate the liver to release some of its store of glucose into the blood. Beta cells work in a complementary fashion, since they are sensitive to high levels of blood glucose and react by producing insulin, an enzyme that has the effect of removing glucose from blood. Through this complementary action of pancreatic alpha and beta cells, blood sugar level is controlled within narrow limits in spite of disturbances provided by fasting, eating, and physical activity. This vital control is conveniently accomplished automatically without awareness or conscious effort on our part.

Blood sugar is just one of the many aspects of our internal environment that must be closely controlled for the normal functioning of our cells. Other essential variables are body temperature, water and salt concentrations, oxygen and carbon dioxide levels, and acid-base balance. It is probably no coincidence that their control provides us with an internal liquid environment that in many respects is similar to the warm sea in which our first single-celled ancestors evolved. As Bernard wrote in 1878, the year of his death:

> The living organism does not really exist in the *milieu extérieur* (the atmosphere, if it breathes air; salt, or fresh water, if that is its element), but in the liquid *milieu intérieur* formed by the circulating organic liquid which surrounds and bathes all the tissue elements; this is the lymph or plasma, the liquid part of the blood, which

> in the higher animals is diffused through the tissues and forms the ensemble of the intracellular liquids and is the basis for all local nutrition and the common factor of all elementary exchanges.
>
> The *stability of the milieu intérieur* is the primary condition for freedom and independence of existence; the mechanism which allows of this is that which ensures in the *milieu intérieur* the maintenance of all the conditions necessary to the life of the elements (Bernard; quoted in Robin 1979, p. 258).

By "freedom and independence of existence," Bernard was not referring to metaphysical freedom of will. Rather he was describing the physical autonomy that allows organisms such as humans to survive in many different and often quite harsh environments despite the chemical and physical fragility of cells that make up our bodies. He saw this control of the inner environment as the primary distinguishing feature of life, what makes life possible and can be understood without recourse to vitalistic principles or phenomena.

It is intriguing to consider that although Bernard was an important proponent of a materialist view of life that made use of then-current knowledge of physics and chemistry, his conception of the organism as a regulator of its internal environment was in an important sense inconsistent with one-way cause-effect models of the physical sciences. If I pour sugar into a glass of water, the concentration of dissolved sugar in the water will increase. If I put a glass of cool water in the warm sun, the temperature of the water will rise. If I apply force to a chair by giving it a shove, it will either slide across the floor or fall over (depending on the amount of friction between chair and floor). These are all examples of the one-way, input-output causality of Newtonian physics in which a physical cause has a direct physical effect.

But Bernard pointed out that living organisms can and do react quite differently to such physical events. If I inject 200 milliliters of a 50% sugar solution into a vein in my arm, my blood sugar concentration may increase for a short while, but the activation of beta cells in my pancreas will soon produce enough insulin to restore my blood to its normal level of sugar. If I leave a cool room to sit in the warm sun (or vice versa), it will have little if any effect on my core body temperature (although the clothes I am wearing will slowly become warmer). And if I give another person a shove, it may well have no effect other than to have him stand his ground and shove me right back.

It seems as if the body actually "wants," "intends," "desires," or "wills" to maintain a certain concentration of blood sugar (90 mg/10 dl), temperature (98.6° F), and physical location (its current one). And it does what it has to to maintain these variables in spite of the types of physical disturbances that would have a noticeable effect on a nonliving object (for contrast, consider what effects these actions would have on a dead body). Although it would always be possible to apply a disturbance so large that the organism would lose control (such as a rapid intravenous injection of a liter of corn syrup, or an eight-hour stay in the sauna, or a shove from a bulldozer), control of important, life-sustaining variables is usually quite well maintained despite many typical disturbances we and other organisms continually confront.

In other words, although he did not describe it exactly this way, Bernard discovered that physiological systems are *purposeful and goal-directed*, designed to maintain constant conditions despite physical disturbances. In this sense, in their stubborn and active resistance, these systems were quite unlike anything that Newton or subsequent physicists had studied. Bernard's unprecedented knowledge of the materialist internal workings of organisms led to an appreciation that they functioned in a purposeful manner to maintain the physical conditions essential for life.

Walter Cannon and Homeostasis

It appears that Bernard's closest associates were much less impressed by this new understanding of the organism's control of its internal environment than they were by his experimental findings listed earlier. It was not until the twentieth century that this knowledge would be appreciated, expanded, and disseminated on the other side of the Atlantic, primarily by Walter Cannon (1871–1945) of Harvard University who, in his research on digestion, was the first to use X rays in the study of physiology. (Like Marie Curie, another pioneer in the use of X rays, Cannon's death was apparently due to the lethal accumulation of radiation he received while conducting his research.)

In his 1932 book *The Wisdom of the Body* (revised in 1939), Cannon published the results of his research team at Harvard's physiological laboratory on the functioning of many mammalian physiological systems, introducing a term that would become universally recognized in the field (1939, p. 24):

> The constant conditions which are maintained in the body might be termed *equilibria*. That word, however, has come to have a fairly exact meaning as applied to relatively simple physico-chemical states, in closed systems, where known forces are balanced. The coordinated physiological processes which maintain most of the steady states in the organism are so complex and so peculiar to living beings—involving as they may, the brain and nerves, the heart, lungs, kidneys and spleen, all working cooperatively—that I have suggested a special designation for these states, *homeostasis*. The word does not imply something set and immobile, a stagnation. It means a condition—a condition which may vary, but which is relatively constant.

In addition to making the concept of homeostasis widely known and continuing the line of physiological research begun by Bernard, Cannon made other important theoretical contributions. One of these was the evolutionary perspective that he brought to homeostasis through which he saw the evolution of "advanced" or "higher" organisms as involving attainment of more sophisticated systems of control. He recognized the influence here of Belgian physiologist Léon Fredericq who in 1885 wrote:

> The higher in the scale of living beings, the more numerous, the more perfect and the more complicated do these regulatory agencies become. They tend to free the organism completely from the unfavorable influences and change occurring in the environment.

Expanding on this idea and obviously influenced by Bernard as well, Cannon noted that "lower animals" such as the frogs can control neither the water content of their bodies nor their internal temperature and can therefore live only in and near water and at moderate temperatures. During cold winter months, a frog must burrow into the mud at the bottom of its pond or lake and remain there until warmer temperatures return. The "more highly evolved" lizard is able to control against loss of water and therefore can live in dry environments like deserts. But because reptiles are also unable to control their body temperature, they, like frogs, cannot remain active when the temperature falls. "Only among higher vertebrates, the birds and mammals, has there been acquired that freedom from the limitation imposed by cold that permits activity even though the rigors of winter may be severe" (Cannon 1939, p. 24). Evolutionary biologists usually refrain from using potentially misleading terms such as "lower," "higher," or "advanced" to compare organisms. Nonetheless, the notion that evolution can provide organisms with increasingly sophisticated control systems is an important insight to which we will return in a later chapter.

Cannon also understood that the mammalian nervous system was divided into two main parts, "one acting outwardly and affecting the world about us [today known as the somatic or 'voluntary' nervous system], and the other [the autonomic nervous system] acting inwardly and helping to preserve a constant and steady condition in the organism itself" (1939, pp. 25, 26). It is here that he appeared to come very close to recognizing that an organism's external actions, like its internal physiological ones, are also part of an essential process of control.

In retrospect, however, one can find serious limits to Cannon's understanding of the control achieved by biological systems. For instance, he provided no formal functional or mathematical analysis of the homeostatic systems he investigated, although he did implicitly recognize that such systems involved the functioning of a circle or loop. Notice, for example, how in the following sentence he begins and ends at the same place—the carbonic acid level of the blood (1939, p. 288):

> If the hydrogen-ion concentration of the blood is altered ever so slightly towards the acid direction, the especially sensitive part of the nervous system which controls breathing is at once made active and by increased ventilation of the lungs carbonic acid is pumped out until the normal state is restored.

On the other hand, Cannon did not explicitly recognize or appear to appreciate the essentially non-Newtonian character of physiological control processes, as is evident in his one-way, cause-effect, push-pull account of body temperature regulation that makes no mention of an internally specified goal state or purpose (1939, pp. 200, 201).

> If conditions are such that there is a tendency to tip the organism in one direction, a series of processes are at once set at work which oppose that tendency. And if an opposite tendency develops, another series of processes promptly oppose it. Thus quite automatically the remarkable uniformity of the temperature of the internal environment is preserved, in opposition to both internal and external disturbing conditions.

Nor did Cannon recognize that many mammalian physiological systems are not strictly homeostatic but rather are capable of achieving and maintaining themselves at different states according to changing needs. This phenomenon, called *rheostasis* (Mrosovsky 1990), is similar to changing the setting on a thermostat resulting in a cooler, though still controlled, room temperature. Despite these limitations, Cannon made a major contribution to understanding the body's "internal wisdom," and his concept of homeostasis eventually found its way into all modern physiology textbooks.