Chapter 10

Homeostasis and Organismic Theory

In a world struggling for unity, borderlines between the different spheres of human thought become unessential. *Thomas Mann*

Vital mechanisms have one object, preserving constant the internal environment. *Claude Bernard*

About the year 1857 Johannes Müller broke down mentally trying to keep abreast of the literature on physiology. *E. J. K. Menge*

10.1: Introduction. This, like Chapters 1 and 25, is an integrating chapter. It discusses a general principle in biology, analogous to the principle of Le Chatelier¹ or the principle of least action in physical science, or to the principle of sufficient reason in philosophy. We must have binding concepts to give us the feeling of orderliness and keep us from developing a Johannes Müller neurosis. The principle is, in brief, that all organisms and also societies of organisms⁵—epiorganisms (Gerard) or supraorganisms (Emerson)—react to changing conditions in such manner as to maintain constant what Claude Bernard² designated as their “internal environment”.

While the body’s powers of adjustment to different conditions have been long known, this knowledge had not become a central principle of physiology—and now of sociology⁵—until Claude Bernard’s dramatic formulation, supported by the penetrating contributions of Haldane³, Loeb⁴, Henderson⁵, Cannon⁶, Barcroft⁷, and many others⁸.

One of Bernard's generalizations is that the degree of an organism's independence of its environment is proportional to its ability to maintain constant its internal environment: la fixité du milieu intérieur est la condition de la vie libre; and that the organism is a closely knit community, the component members of which are organized to keep the internal environment constant in the face of fluctuating external conditions (examples of "physiologic constants": blood pH, body temperature, blood pressure, pulse rate, etc.).

We shall employ Cannon's designation homeostasis to describe this principle, this tendency to maintain a "steady state" (homeo from the Greek, like or similar; homoio, the same).

Homeostasis, the integrated cooperation of all the organs and systems in the body—nervous, endocrine, circulatory, excretory, digestive, and so on—in the maintenance of a "steady state" equilibrium may be considered as one aspect of what is often referred to as organicism, holism, gestalt, and related concepts including, on other planes, perhaps dialectic materialism, multiple causation, and so on.

While some phases of adaptation of organism or supraorganism may be considered as special cases of the theorem of Le Chatelier, formulated for non-living systems, homeostasis is reserved for biologic (and sociologic in this book) changes which do not necessarily occur in the same direction, as they would in a non-living system. Thus changing environmental temperature does not necessarily change body temperature but sets in motion thermo-


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regulatory apparatus to counteract the external change (Ch. 11). Administration of thyroxine to normal individuals does not necessarily increase the metabolic rate, but sets in motion mechanisms for suppression of the body's own thyroxine production (Ch. 7). Reducing oxygen pressure in the air (by climbing a mountain, or in a low-pressure chamber) does not necessarily reduce the oxygen supply to the cells but sets in motion regulatory changes (such as increasing the hemoglobin concentration in blood and other oxygen-carrying mechanisms and—the latest observation—probably increases the concentration of the oxidation catalysts in the body as indicated, for example, by increased excretion—and therefore production—of ascorbic acid in rats on placing them in a low-pressure chamber). Biologic reactions are, evidently, not always explicable on the customary physical or chemical levels (Ch. 16) but on unique organizational levels which may not be present in non-living systems. This appears to be recognized as indicated by the following remarks: life is not a characteristic of atoms, molecules, or genes as such, but of a certain organization of the parts of the living organism (E. G. Conklin); the laws of physiology are laws of organization (Claude Bernard); physiology is concerned with sociological laws, laws of organization and adaptation (A. Carrel); the unique problem of physiology is to discover the relatedness to one another of the details of structure and function (J. S. Haldane). Darwin has said that evolution is change in form in successive generations in response to certain influential factors in the environment.

The concept of homeostasis, especially if it is extended to include societies of organisms as well as individuals, has very far-reaching implications. Indeed, every one of the preceding and following chapters is an illustration of the effectiveness of homeostasis. Thus the following chapter is concerned with homeothermy, the homeostatis of body temperature. Chapter 24 deals with homeostasis in muscular work, that is, the maintenance of a constant level of oxygen and carbon dioxide in the blood in the face of greatly increased oxygen consumption and carbon dioxide production during heavy muscular exercise. Chapters 13 to 15 discuss the homeostasis of metabolism in relation to surface area and to change in form. Chapter 17 is concerned with homeostasis in relation to the ratio of surface area and of strength of the supporting structures to increase in body weight. Chapter 16 deals with the homeostasis of growth: growth proceeds as if the "normal" condition were that represented by the mature size, and the rate of growth tends to be proportional to the distance from the mature size. Chapter 18, on senescence, is concerned with failing homeostasis; and so on, as illustrated by some of the following sections which could be expanded indefinitely.

Pathology may be considered as the study of attempts to maintain homeostasis under conditions of injury. When injury occurs, processes are set in motion to correct it. The tendency to wound healing is, indeed, so great that we pay little attention to it. Even a heart afflicted with coronary sclerosis
(Ch. 18) may function for many years by various compensations, even to the extent of establishing new collateral circulatory vessels to take over the functions of the sclerotic ones. Reproduction of the organism as a whole, as of its constituent cells, may be considered as a compensatory, or homeostatic, mechanism against senescence, maintaining constant the internal social environment in spite of the aging of its constituent members.

The study of homeostasis is, then, the analysis of factors that maintain an advantageous dynamic steady state in biologic systems in the face of conditions that oppose it.

Let us discuss a few illustrative homeostatic mechanisms in detail. In the interest of simplicity each of the following sections is devoted to a different homeostatic mechanism. These mechanisms do not, however, necessarily function independently.

10.2: Body-weight regulation. Some readers may recall that their body weight had not changed as much as five pounds over many years, in spite of widely differing conditions of life. Some may also recall the difficulties encountered in attempting to increase or to decrease body weight. The body appears to have automatic regulatory, or homeostatic, mechanisms stronger than purposive resolves to change body weight. Two or three of these mechanisms have been investigated.

One, the decline in digestibility, metabolizability, and assimilability (or increased losses in feces, urine, and heat increment of feeding, or SDA) has been discussed (Ch. 5). The more food consumed, the less the nutritive utilization per unit food; conversely, the less food consumed (within certain limits), the higher the utilization per unit food.

Then, too, the higher the food intake, the higher the body weight and, therefore, the greater the proportion of the food that goes to maintain the body; conversely, the lower the food intake and the lower the body weight, the less it costs to maintain the body. In brief, the dietary maintenance tax is adjusted to the dietary input; when placed on a reducing diet the organism becomes more economical, thus counteracting weight reduction; on an abundant diet, the organism becomes more and more extravagant, counteracting undue fattening. The body persists in maintaining its "normal" weight.

Our colleague Addison Gulick, characterized by a spare or non-fattening type of "normality", reported in a dramatic manner his strenuous but relatively unsuccessful attempts to gain weight. Gulick "explained" his unsuccessful attempts to gain weight by referring to "spendthrift oxidation"

14 For a recent discussion of the physiologic mechanisms adjusting intake to output, or gains to losses, of body weight, including water, energy, and nitrogen, see Gasnier, A., and Mayer, A., *Ann. Physiol. Physicochim. biol.*, 16, 145, (1939) (nature and number of regulatory mechanisms); p. 157 (nutritional regulatory mechanisms in the rabbit); p. 186 (regulatory mechanisms of metabolic intensity); p. 195 (breed differences in rabbits); p. 210 (individual differences).

during overnourishment” and “economical oxidation during undernourishment”.

Anderson and Lusk investigated the efficiency of a dog working under various conditions of food supply. The dog showed greater energy expense when in an overnourished than in a spare condition. Zuntz and Loewy reported 10 and 16 per cent reductions in their basal energy metabolism when placed on the spare German war diet. Benedict and associates reported 20 per cent reduction in basal energy metabolism in young men on a reduced diet involving a loss of 130 g nitrogen.

All in all, the body has very effective automatic mechanisms to prevent interference by purposive meddlers with its normal, that is, its hereditary, weight.

The homeostatic regulation of body weight is evidently of great agricultural importance. High feeding accelerates the fattening process, but it occurs at a greatly increased energy cost; conversely, the leaner the animal at the beginning of a fattening trial the more economic its gains. In general, the economy of gain tends to be proportional to the distance from the “finished condition” (Chs. 5 and 22).

Though we are not here concerned with detailed causal mechanisms, it may be noted that the immediate hunger mechanism was shown by Cannon and by Carlson to consist of contractions of the stomach walls. The contraction hunger pain is reinforced by appetite, psychic longing for the remembered sensation of feeding.

Bulato and Carlson reported that hunger contractions may be produced at will by reducing the blood sugar by insulin injection, indicating that reduction of blood sugar produces the stomach contractions. There is no doubt that food consumption and weight gains are greatly increased by administration of insulin in proper form (protamine zinc insulin). However, it has not been proved that the normal hunger sensations are caused by lowering the blood-sugar level. But whatever the mechanism, it is effective in maintaining the body at its hereditary weight level.

10.3: Body-water regulation. The fat-free body of cattle contains about 70 per cent water in adults, 90 per cent in the early prenatal period of growth. If the fat is included, the water percentage tends to vary inversely with the fat content, since muscle contains 75 per cent water, whereas the fat depots contain only 6 to 20 per cent. The early embryo, which has little fat, contains up to perhaps 90 per cent water, while the very fat mature steer may contain but 40 per cent water. The various constituents differ in their water content: 99.5 per cent in saliva; 99 per cent in cerebrospinal fluid; 85 per cent in brain gray matter, 68 per cent in brain white matter; 79 per cent in blood; 75 per cent in muscle; 72 per cent in skin; 60 per cent in bone.

Water is being continuously lost through kidneys, alimentary tract, exhaled air and skin. These losses are made good by the automatic thirst mechanism, just as losses in body weight are made good by the hunger mechanism.

When excess water is ingested, the body keeps this water from diluting its internal environment by excretion and by storing it in the muscles and skin which constitute water reservoirs. Thus Haldane and Priestly reported that of 5 liters water taken between 10:45 and 1:15 p.m., 3.2 liters were excreted in the urine by 3 p.m. Apparently none of the remaining water in the body (equivalent to 40 per cent of the blood volume) was found in the blood. There is considerable evidence that the muscle and skin store the excess water temporarily.

Adolph reported that the rate of water excretion is proportional to its excess above the normal level and the rate of water intake is proportional to its deficit below the normal water level.

10.4: Carbohydrate-level regulation. Man does not tolerate a decline in blood-sugar level below about 80 or 70 mg per cent, and if it rises above 160 mg per cent the blood sugar spills over into the urine. The blood sugar in post-absorptive condition is normally 90 to 100 mg per cent, and after a meal about 130 mg per cent. How does the body regulate the blood-sugar concentration within these narrow limits, considering the large quantities of sugar thrown into the blood after a substantial meal, oxidized during heavy muscular exercise, or tapped off during milk production?

References:
Claude Bernard's researches on the blood-sugar level led to his generalization at the head of this chapter. Bernard's conclusion, amply substantiated, is that the excess glucose is converted into insoluble glycogen and fat. The liver is the major glycogen-storing organ, accounting for from one-fourth to over one-half the total body glycogen; the remainder is distributed in the muscles. The glycogen is reconverted to glucose and fed back to the blood at a rate required to maintain the blood-glucose constant. Insulin (from the islets of Langerhans of the pancreas) is the major hormone involved in this conversion. The blood-sugar level is also regulated by the pituitary (glycotropic hormone), thyroid, and kidney. In addition, the nervous system is involved, by serving as medium of transmission and communication for the bodily needs. The sympathoadrenal system is involved in sugar mobilization in emergencies (see Cannon).

While excess sugar in the blood does not produce important subjective symptoms, blood-sugar deficiency leads to feelings ranging from hunger through nervousness and weakness, to convulsions following an excessive dose of insulin injection (insulin or hypoglycemic reactions). Objective symptoms are pallor, rapid pulse, dilated pupils, profuse sweating, and convulsions. The brain obtains its energy perhaps exclusively from sugar. For this reason, in part, sugar deficiency in blood, for example, insulin hypoglycemia, leads to serious nervous disturbances (Sect. 20.2).

Blood-sugar regulation declines with age following 30 or 40 years, perhaps because of defective glycogen storage in the liver.

10.5: Calcium-level regulation The parathyroid hormone (parathormone) is the principal regulator of calcium-metabolism (Ch. 7), analogous to insulin, the principal carbohydrate-metabolism regulator. The percentage range of the calcium level in blood (9 to 12 mg per cent plasma) is of the same order as the percentage range of glucose in the blood (80 to 130 mg per cent). There is the additional limitation that the product of calcium and phosphate ions should be constant (in serum the product of Ca and of P in mg is about 36 and the Ca/P ratio between 1 and 2). In other words, the proper functioning of calcium metabolism is also dependent on a certain phosphate concentration, and it might be added, on a certain concentration of parathyroid hormone, vitamin D, and phosphatase enzyme.
The equilibrium between calcium ion on one hand and insoluble bone \([\text{CaCO}_3 \cdot 2 \text{H}_2\text{O}] \text{ to } 3\text{Ca}_3(\text{PO}_4)_2\) on the other, is analogous to the equilibrium between blood sugar and glycogen.

Just as hypoglycemia affects the nervous system (mostly the cortical function), so hypocalcemia affects the nervous system (mostly the autonomic and peripheral nervous systems). Milk fever (in dairy cattle) is a familiar agricultural example of hypocalcemia.

10.6: Fat-level regulation. The blood contains lipoids in the form of total fatty acids or “total lipid” 300 to 500 mg per cent; cholesterol esters 150 to 190 mg per cent; lipid phosphorus (lecithin) 12 to 14 mg per cent; or phospholipid about 140 mg per cent (in plasma) to 420 mg (in corpuscles). However, very much higher values were recorded in essential hyperlipemia. Ingestion of a meal of fat results in “alimentary lipemia”, associated with a rise of fat in blood to 2 or 3 per cent.

As sugar or calcium concentration remain nearly constant by storing or drawing on glycogen or bone, so the lipoids remain roughly constant by storing fat in various fat depots when there is excess of it, and drawing on these fat depots when there is scarcity of food.

The physiologic control of lipoid transport has been investigated most extensively by Bloor. As a calcium hexose monophosphate is the important intermediary in calcium metabolism and calcium homeostasy, so lecithin, also a phosphorus-containing substance, appears to be the important intermediary in lipid homeostasy. It was noted (pp. 128 and 133) that lecithin (or choline) deficiency leads to the formation of fatty livers and “cholesterol livers”.

10.7: Oxygen and acid level regulation. The process of living involves the consumption of enormous quantities of oxygen and production of equivalent quantities of acids (carbonic, sulfuric, phosphoric, etc.). Yet both oxygen and acid levels deviate insignificantly from the “normal” level even during...
muscular exercise, when the oxygen consumption and carbonic acid production may increase ten-fold (Ch. 24). This constancy of internal environment is brought about by several mechanisms, from increased ventilation rate and circulation rate (Ch. 24) to increased hemoglobin concentration. Thus ascending Mount Everest about 20,000 feet, where the oxygen pressure is 50 per cent of that at sea level, the blood hemoglobin may increase from 4 million cells/cc to over 8 million. Moreover, a hemoglobin unit in high-mountain dwellers can carry more oxygen, as illustrated by the following data from Dill on high-mountain dwellers.

<table>
<thead>
<tr>
<th>Vicuna (high-mountain dweller)</th>
<th>Man</th>
<th>Domestic Sheep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume % arterial $O_2$</td>
<td>18.0</td>
<td>14.4</td>
</tr>
<tr>
<td>Volume % venous $O_2$</td>
<td>4.0</td>
<td>2.4</td>
</tr>
<tr>
<td>Difference</td>
<td>14.0</td>
<td>12.0</td>
</tr>
</tbody>
</table>

Then, too, under sudden demand for oxygen the blood stored in the spleen and liver is released to help with the oxygen transport. Barcroft reported that the spleen of a dog was reduced to ¼ normal size when the dog was set to chase a cat. Scheunert and Krzywanek reported increased blood counts in horses during exercise. Rein reported that the liver released 25 per cent of its blood under the influence of adrenaline. In brief, exercise and other conditions which involve increased oxygen use are associated with increased hemoglobin concentration.

It is interesting to recall that in the later stages of gestation fetal growth proceeds at an increasingly relative faster rate than the placenta, resulting in decreased oxygen supply to the fetus. The blood picture of the new-born shows the effects. This prompted the remark (by Barcroft?) that during the last stages of gestation the embryo lives in a Mount Everest atmosphere and is acclimated to it. For this reason, in part, new-born and very young animals have very high hemoglobin concentration and, in general, tolerate anoxia very much better than older ones (Ch. 14).

The exceptional ability of whales, seals, and beavers to remain submerged for half an hour depends (Ch. 24) on these homeostatic reserves: large blood volume, high hemoglobin concentration, the ability to go into great oxygen debt, and especially the ability to shunt the blood (which carries the oxygen) to the central nervous system (most sensitive to oxygen want) from the other tissues, those less sensitive to oxygen want. Anoxia is also associated with

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33 Dill, D. B., "Life, heat, and altitude," Cambridge, Mass., 1938. Altitudes and air pressures: Mount Everest having an altitude of about 29,000 feet, has an air pressure which is about 35 per cent of sea-level pressure; Pikes Peak, 13,000 feet high, about 60 per cent sea-level pressure; Mexico City or Santa Fé about 8,000 feet, about 78 per cent sea-level pressure; Denver, about 5,000 feet, about 83 per cent sea-level pressure. Hall, F. G., Dill, D. B., and Barron, E. S. G., J. Cellular and Comp. Physiol., 6, 301 (1936). Barcroft, J., also J. Physiol., 68, 375 (1930). Izquierdo, J. J., and Cannon, W. B., Am. J. Physiol., 84, 645 (1928). (Fear and rage increase red blood count.)
lowered body temperature and, therefore, reduced metabolism and depressed oxygen need.

Since lack of oxygen and lack of glucose have the same end effect on brain metabolism, the nervous symptoms described for hypoglycemia also hold for anoxia.\textsuperscript{42}

The mechanism of blood-acidity regulation was worked out chiefly by Henderson\textsuperscript{43, 44} and Barcroft\textsuperscript{43}. The blood pH ranges only\textsuperscript{45} from 7.30 to 7.45. Even feeding sulfuric acid (over a liter a day of $\text{H}_2\text{SO}_4$ to hogs\textsuperscript{46}) did not change it.

The maintenance of constant pH of the blood is accomplished by (1) preliminary neutralization by the blood buffers (bicarbonates, phosphates, hemoglobin, and also by ammonia), (2) excretion of the volatile acids ($\text{CO}_2$) by the lungs, and (3) excretion of the non-volatile acid by the kidneys.

**10.8: Neuro-endocrine homeostasis.** We have seen (Ch. 7) that if the metabolic hormone thyroxine is injected, the body “tries” to keep the metabolic level constant by reducing its own production of thyroxine. Similarly, if the sex hormone estrogen is injected, the animal “tries” to maintain its normal sex activity level by reducing the production of its own estrogen.

Both of the controls are carried out by way of the pituitary, by depressing the production of thyrotropic and gonadotropic hormones respectively. The same mechanism is employed for many other hormones controlled by the pituitary.

Dairymen know that milking stimulates and cessation of milking depresses milk production. Now milk production is dependent on pituitary lactogenic hormone production, and it appears\textsuperscript{47} that suckling stimulates it, obviously by a nervous path. The closely related maternal reflexes are even more intimately dependent on the central nervous system, including the higher brain centers\textsuperscript{47}.

The dietary control of insulin production is interesting. On heavy feeding, the islets of Langerhans hypertrophy, producing more insulin to take care of the excess sugar. However, this often sets up a vicious cycle: the more food, the greater the hyperinsulinism and the greater the hyperinsulinism the greater the desire for food. This leads to obesity and frequent degeneration of the islets of Langerhans due to overwork\textsuperscript{48}. Here we have a type of homeostasis which by its immediate correction leads to ultimate failure.

\textsuperscript{42} Himwich, \textit{et al.},\textsuperscript{29} (1939), Barcroft\textsuperscript{39} (1938), Gellhorn\textsuperscript{8} (1943). Van Liere, E. J., "Anoxia", Univ. Chicago Press, 1942.


There are other examples of the same type. Thus strong emotions lead to nerve excitation (parasympathetic, vagi, sacral) and production of excessive amounts of acetylcholine, sympathin, histamine, adrenaline, and so on favoring the overcoming of the immediate emergency but often with unfavorable long-range effects (Ch. 18) on the circulatory and digestive systems. Exophthalmic goiter is attributed by Crile (Ch. 18) to over-excitement.

A familiar example of the effect of nervous stimuli on endocrine activity, which has a homeostatic basis, is the mobilization of sugar (hyperglycemia) during emergency to furnish the energy for the forthcoming effort; if the effort does not materialize on a physical plane (as in the case of a spectator at a foot-ball game who does not himself fight although emotionally geared thereto), the sugar is eliminated by the kidney, constituting the well-known emotional glycosuria, thus keeping the blood sugar level constant (Cannon's emergency theory 49, see Sect. 7.3.2B).

Some emotions become habitual, chronic, "structured", or conditioned, such as those investigated by Pavlov 50. These are of great agricultural as well as social importance. Good animal husbandmen appreciate the importance of gentle treatment of their animals, and are aware of the unpleasant conditioned reflexes, or habits, that may develop, especially in horses and dairy cattle. As Mark Twain has said, habit is habit, not to be flung out of the window by any man.

Rapid salt loss due to any one of many causes, such as adrenalectomy 51, diabetes insipidus 52, or sweating is associated with corresponding craving for salt 53. On the other hand, extreme salt consumption is often a diagnostic symptom of adrenal and related diseases. Indeed, it has been suggested that taste thresholds may serve as delicate indices of nutritional deficiencies 54.

Parathyroidectomy, which disturbs calcium metabolism, is associated with greater (four-fold) calcium (lactate) intake 55. In the absence of calcium more magnesium and even strontium salts are consumed. During pregnancy and lactation protein and mineral (but not carbohydrate) intake is increased 56.

Vitamin B is essential for carbohydrate oxidation; hence the aversion for carbohydrate (and protein) and craving for yeast on a vitamin B-deficient diet 56, 57. However, this homeostatic mechanism does not function precisely.

\[\text{\cite{Richter, C. P., and Eckert, J. F., Endocrinology, 22, 214 (1938).}\]
\[\text{\cite{Richter, H. G., Science, 90, 67 (1939).}\]
\[\text{\cite{Richter, C. P., Endocrinology, 24, 367 (1939).}\]
\[\text{\cite{Richter, and MacLeod, A., Am. J. Physiol., 128, 1 (1939).}\]
\[\text{\cite{Jukes, C. L., J. Comp. Psychol., 26, 135 (1938).}\]
Thus chickens do not differentiate between riboflavin-rich and riboflavin-poor diets even if they are riboflavin-starved. Many other examples could be cited.

Appetite, then, appears to be in many cases, but not in all, an important guide to "nutritional wisdom" or homeostasis, provided that it is not conditioned adversely in early life. The wide popularity of "sweets" and white bread may be the result of early conditioning by a wrong "psychodietetics". It is interesting to note that such animals as dairy cattle and high-laying fowl raised under relatively artificial systems rather lack nutritional wisdom, and the same is true of children (Sect. 20.5).

10.9: Social homeostasis. A multi-cellular organism may be viewed as a community of individual cells specialized to perform various functions for the community as well as for carrying out their own basic metabolic or life processes. Such a viewpoint suggests an analogy between an individual multi-cellular organism, for example an ant, termite, or bee, and a society of organisms, or supraorganism, for example, a colony of ants, termites, or bees. The multicellular individual termite is derived from a single egg cell. The cells of the individual differentiate, by virtue of their positions in the body, into the various specialized cells and tissues. Similarly, the colony of termites or bees is derived from virtually a single egg cell, the individuals of which differentiate, by different feeding methods and other conditions, into various specialized individuals—workers, soldiers, drones, queens, and so on.

In some species at some time it is indeed impossible to distinguish between a multicellular individual and a closely integrated group of individuals. Not only are the two categories alike in being composed of the same ultimate substances, carrying on the same metabolic processes, having similar adaptive mechanisms, but both are stages in the evolution of ever larger and more integrated "orgs". It will be shown (Chs. 16 and 19) that the age curves of growth of individuals, such as rats or pumpkins, are so similar to the time curves of growth of populations (of yeast, bacteria, flies, men) that all the curves can be made to coincide.

This analogy between the individual organism and society of organisms extends to social homeostasis, of which social insects (such as termites, ants, bees, and so on) furnish striking examples on one organizational level. But one may cite examples of homeostasis on many different levels and in different categories, indicated by the following illustrations.

The reproductive function attains peak activity when growth approaches its end (Ch. 16), that is, when the individual organism begins to get old. Sexual virility may thus be said, figuratively, to coincide with approaching individual senility (Ch. 18). The lawn grass goes to seed most readily when individual life is threatened and on the decline (as in drought, etc.). Reproduction of the individual may thus be viewed as a phase of social homeostasis. By reproduction the "internal environment" of the social organism is kept constant in spite of the aging and dying of its constituent members. Reproduction is a social homeostatic mechanism.

The reproductive process (Ch. 7) is extremely complex and, needless to say, the individual plant or animal does not foresee the social-preservation, or sociocentric, "purpose" of its reproductive drive, just as it does not foresee the individual-preservation.
or individuocentric, “purpose” of its hunger and thirst drives. But the ultimate functional aim appears to be to maintain constant the “internal environment” of the social and individual organisms respectively.

The homeostatic mechanisms appear to evolve to ever finer organizational levels. Thus (Ch. 8) reproduction is adjusted, in the social interest, to function in such seasons of the year as will give the new-born animal the best opportunity for survival.

The development, in the most evolved animals (mammals), of the uterus and of mammary methods of raising the young is another illustration of the increased perfection of social homeostasis with advancing evolution. Instead of dropping the unfertilized eggs in the ocean as a fish does, the highly evolved mammal houses and nurtures the young in an especially evolved body cavity; then, after birth, gradually bridges the young to independent life by feeding it with the special mammary secretion. The dairy industry is, of course, based on the exploitation of this evolutionary mammary development.

This type of reproductive method develops family life. Family life is also strong in many bird species, especially those like pigeons, which produce “crop milk”, and as previously noted on a different organizational level, in social insects. But it is, perhaps, on the highest level in mammals, particularly in man, who is distinguished from other mammals by a higher level of consciousness and by the ability to raise children of different ages simultaneously. Thus a special type of social life evolves, leading to the development of the uniquely human social characteristics of patience, forbearance, and charity on the part of the older and stronger children toward the younger and weaker. These newly evolved characteristics may be called moral or ethical, and are destined to play an ever greater part in the evolution of human social life if the human species is to survive.

In man we see the family idea, with its higher level of conscious homeostasis, develop into ever larger aggregations—tribe, clan, nation, and finally, perhaps, a world federation. These broader human aggregations are made possible by the unique human ability for abstract thinking and communication in symbolic terms—language. By such communication men learned to recognize, in an impersonal way, the relatedness of all mankind. These unique recognition qualities in man have a structural basis in his nervous system. Primitive animals and primitive functions in higher animals are controlled by the autonomic nervous system concerned primarily with adjustment between organs within the individuals; the higher functions in the more evolved animals are controlled by the central nervous system, especially by the brain and more particularly by the fore-brain, the cerebral cortex, concerned with adjustment of the organisms as a whole to distant environment. The development of the brain reached enormous proportions in man with correspondingly far-reaching recognition qualities. The brain weight (by no means the only index of high development) in a 150-lb man is over three pounds, whereas that in 1500-lb cattle is less than one pound (Ch. 17). Indeed, with the exception of the whale and elephant, man has the largest absolute brain. (Fig. 10.1).

The extraordinary brain development in man and his unique abstract or symbolic method of communication and preservation of accumulated knowledge, introduced a new factor in evolution, not dependent exclusively on genetic modification. The genetic make-up of man is certainly the same today as it was 200 years ago—and perhaps 20,000 years ago—and yet what transformations have occurred in human life, due to the development of science! Indeed, the automobile, telephone, electric light, radio, hydroelectric power, airplane, submarine, bombers, poison gases, not to speak of the gang plow and tractor, cream separator, combine harvester, chemical fertilizers, immune sera, anti-toxins, prefabricated houses, and so on, developed within the writer’s memory. The evolution and integration of human society has thus become disengaged from genetic change, although it may lead to *purposive* genetic change. The future course
of the evolution of man is in the hands of man himself, and it is difficult to predict what he will do with himself.

His future becomes ever more unpredictable by the very development of his abstract methods of thinking and communicating and by his science and invention. Thus an abstract idea, perhaps biologically destructive and therefore humanly senseless, if rationalized in words which appeal to emotional residues, may precipitate a world war and all but destroy man and his works. World War I is said to have cost in goods the equivalent of 340 billion dollars and some 33 million human lives in military and civilian casualties. The present better and bigger World War II, it is estimated, will cost at least the equivalent of 1000 billion dollars in goods and 50 million in military and civilian casualties. And who can predict what the third world war will cost and whether human society will react to these changes "so as to bring itself to normal"?

This calls attention to a curious characteristic of the average man: that while he thinks himself logical enough to have "common sense", he is often devoid of it. It

![Graph](https://via.placeholder.com/150)

**Fig. 10.1** The relation between the average brain weight of mature man and of the average brain weight of mature mammals of other non-anthropoid species ranging from mice to whales. Man's brain weight is almost as large as the elephant's.

took not the "common sense" of the average, but the uncommon sense of the rare "impractical" scientist to demonstrate that the earth is not flat, and so on for nearly every astronomic and other scientific discovery. Words, or language, may be used for illogical as well as for logical ends. This is generally known to psychologists.

Most of us are, indeed, familiar with "psychologic warfare", the "war of nerves", and with the concept of "rationalization". Like other human inventions, language may be used for good or evil, for healing or for wounding, for peace or for war.

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61 There is a growing literature on non-logical thinking. For the most elaborate book on non-logical patterns of human action, one which may have encouraged the rise of Fascism and Nazism, see Vilfredo Pareto, "Traité de sociologie générale," Paris, 1917, or Pareto, V., "The mind and society," New York, 1935. For more recent books, see among others, Korzybski, A., "Science and Sanity," The Science Press, 1933; Baynes,
Social homeostasis in man, as it relates to the balance between peace and war, appears to be roughly as follows. Animal evolution, including that of man, involves two opposing drives: (1) an egoistic (strutting, fighting, various "pecking-orders," and other forms of egocentric self-aggrandizement) and (2) an altruistic (sex, parenthood, family, flock, herd, tribe, clan, nation, and perhaps supernation, and other forms of sociocentric activity).

Allee and colleagues emphasized the relatively greater altruistic than egoistic drives in evolution; otherwise the more highly evolved animals and animal societies could not have evolved because the animals would have destroyed each other under the compulsion of the self-aggrandizement drive. This may have occurred in some species that developed particularly effective fighting weapons (as saber teeth in the saber-tooth tiger), and this may be the case in contemporary man with his scientific weapons.

Paralleling the development of man’s increasing powers for destructive warfare, as a result of his thinking on abstract levels, there also developed in all human civilizations a unique altruistic power on an abstract level, one which goes under the general name of "religion". Omitting for the present purpose the ritual and supernatural aspects of religion (without, however, minimizing their importance as carriers of altruistic action), its basic features are humility, counteracting the strutting and related self-aggrandizement drives, and neighborliness or the Golden Rule, counteracting the fighting and related pugnacious drives.

These two basic features of all religions, no matter how worded, are generally accepted not only by the leaders of conventional religious sects but also by philosophers and biologists who have outgrown the stage of so-called conflict between science and religion. In brief, it appears that religion is a social homeostatic phenomenon evolved on a characteristically human level of symbolic thought, as war is evolved on a characteristically human level of abstraction. This homeostatic mechanism, religion, has not been functioning well in recent years, and it is suggested that it be investigated on the characteristically human level, scientifically, to set it aright, so as to serve its function in keeping in check destructive forces in the form of world wars. The greatest immediate need seems to be the development of methods for selecting leaders who will utilize the tools of science, which grow cumulatively ever more powerful, for peaceful construction rather than for warlike destruction.

10.10: Notes on organismic or field theory and on research methods. The living body’s building stones, the electrons, protons, atoms, and molecules, are no different from those in non-living systems. But in virtue of its peculiar

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62 Allee, W. C., Science, 97, 517 (1943).
63 Kettering, Charles F., "You chemists are more or less responsible for this war", Chem. and Eng. News of the A.C.S., 21, (1943).
64 A. N. Whitehead, philosopher and mathematician, writes: "Science is concerned with the conditions which regulate physical phenomena, whereas religion contemplates moral and aesthetic values. On one side there is the law of gravitation; on the other, the contemplation of the beauty of holiness". W. C. Allee, a biologist, states: "To me 'God' is a . . . name for the personification of all the best that the human race has been able to think and do and of all the beauty we have created, together with all the natural beauty we can appreciate; and religion as . . . unselfish living and honest thinking . . . " To the author, religion seems best defined by: the consecrated devotion to the values and/or to the faiths which seem to promote the best interest of humanity.
organization the organism as a whole is in a different category from that of non-living systems. In general, the biological form of order is different from those found in non-biologic systems—"it is a new dialectic order".

The organismic or field hypothesis in biology is similar in intent to the field theory of the newer physics. Just as the "field" in physics is an electromagnetic integrative process, so the "field" in biology is an integrative process binding the many components into a whole, perhaps at different levels (Ch. 17). The characteristic of the field pattern as defined by Weiss is that it tends to be restored on disturbance, which is also the definition of homeostasis.

The existence of a stable field pattern during growth and development may be demonstrated experimentally. It was pointed out (Chs. 7 and 16) that an egg, or even a gastrula, may be divided into several parts, and that each part may develop into a complete individual. This indicates that the destinies of the parts of the embryo are also shaped by the environment, and by the field pattern which restores itself after being cut up into parts. This was substantiated in another way by Spemann, who demonstrated that prior to the gastrula stage head formation may be induced in either head or tail region under the influence of a hormone-like head organizer, or under the influence of another field, by transplantation (see Sect. 7.8.2).

In a later stage, however, tissues no longer respond indiscriminately to organizers; each tissue develops a characteristic response, and the formation of head or tail depends not only on the nature of the organizer, but also on that of the tissue competence. Thus, at first, any part of the neurula could develop gills; later only a special gill area is capable of developing gills.

These ideas on individual (ontogenetic) loss of plasticity with advancing age may be extended to species (phylogenetic) loss of plasticity with advancing evolution. Primitive organisms have greater potentialities for diversification than more evolved forms; a given species is such not because it was evolved from a given evolutionary predecessor but because, in addition to the proper potentialities of the predecessor for the given type of evolution, the predecessors were subjected to environmental influences and field structures which acted as "evocators" or "organizers" for the given evolutionary course of the species (see Sect. 7.8.1).

As growth proceeds and the tissues and organs become ever more specialized, they necessarily become further separated from one another in space and time because of the differential rate of aging of tissues and organs. The various specialized organs are, however, closely integrated by organismic devices, such as the nervous, circulatory, endocrine and other systems.

What was said about ontogenetic specialization and spatial separation is applicable to phylogenetic specialization and spatial separation, with con-

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65 Frank, L. K., Philosophy of Science, 2, 210 (1935).
sequent greater need of integration by increasingly complex organismic devices.

Schmalhausen remarked that the greater the degree of specialization of parts of an organism, the greater the degree of their interdependence and the higher the integration level. High specialization of structures and functions must necessarily be associated with high organismic integration if the organism is to survive. The same idea was expressed by many others.

Since a highly specialized organism is a closely interrelated field-structure, it follows that when a tissue, cell, or molecule is removed from its field, it no longer exhibits its normal "organismic" characteristics. Consequently, the usual method of experimental investigation of growth is in a sense artificial because it separates the unified growth process. Experimentally, however, the whole is often best approached through a study of its parts. The study of parts often leads to valuable intellectual syntheses of the whole. Such, in fact, is the history of many scientific syntheses. The configuration of the atom as a whole was learned by splitting it into parts. The discovery of many vitamins and hormones and of their interrelations was accomplished in some respects by artificial "split-field" methods. The "split-field" method of research may be philosophically objectionable, but in practice it is unavoidable.

Other methodological problems have been raised since the development of the field, organismic, and relativity concepts, indicated by the following illustrations.

One of these is known as the principle of uncertainty or indeterminacy formulated by Heisenberg in 1926, to the effect that the observed system is altered by the observation of the observer.

This Heisenberg Principle was formulated for small-scale (e.g., motion of electron) events. To illustrate, an electron is observed with the aid of the light of another electron. This light influences to an unknown extent the behavior of the observed electron, so that it is impossible to observe a given electron unaffected by the observation light. That is to say, the observer is a part of the observed system, and the measured object is altered by the act of measurement itself.

This principle, based on small-scale observations, may be extended to large-scale observations whenever the act of observation alters the measured object. Thus it is not possible to determine the precise chemical constitution of a living cell, inasmuch as the attempt of the observer to observe the cell (by chemical analysis) alters the observed system (by killing it). Of course, this is rather an extreme example.

The application of Heisenberg's deductions from small-scale events (elec-
trons, protons) to large-scale events may be illustrated more cogently by examples from Compton\textsuperscript{70} and Lillie\textsuperscript{71}. Nerve impulses, electrochemical in nature, are small-scale events, as, for example, those resulting from the impingement of light protons on the eye. The organism acts as a powerful amplifier which sets in motion large-scale events. Consequently, the large-scale end-result may have uncertainties of the same order as the small-scale events.

While the behavior of small-scale events at a given moment is not definitely determined, it obeys the laws of probability. "The quantities which appear in its [quantum mechanics] laws make no claim to describe physical reality but only the probability of the appearance of a particular event" (Einstein). This generalization is in a sense applicable to all measurements and predictions, which is one reason for the use of statistical methods in the analysis of experimental data.

Large-scale uniformities, which constitute the subject matter of scientific laws, may be considered as statistical averages of small-scale or "atomic" diversities. Thus, while it is not possible to predict individual durations of life, yet, judging by the practical success of life insurance companies, it is possible to predict the average expectation of life. The immense practical success of science and industry based on scientific laws testifies to the average orderliness of events. In view of this evident orderliness, the following unqualified opinion\textsuperscript{72} seems misleading. "The universe is ... without unity, without continuity, without coherence or orderliness ... Order, unity, and continuity are human inventions just as truly as are catalogs and encyclopedias ... Such orderliness as we appear to find ... seems to be due to our passion for pigeon holes, and it is quite doubtful whether there are such things as laws of nature". The view that the world is an interrelated dynamic configuration seems more reasonable. Perhaps the following remark by Hyman Levy represents more nearly the situation: "The world is an enormous interrelated dynamic muddle with intermittent patches of order and sanity".

The problem of uncertainty discussed above leads to the problem of the methodology of mathematical analysis of experimental data.

Now mathematics has two aspects: theoretical, not dependent on reality, and applied, which is very real indeed. The two aspects are illustrated by the following quotations and discussions.

"Mathematics is not science; it is not nature, unless it be in the nature of the mind; it is not concerned with the truth but only with the exactness of the deductive process. Is the formula $50 \times 2 = 100$ true or false? The answer depends on circumstances. It is true when applied, for example, to 50 apples in one basket and 50 in another. It is debatable when applied, for example, to temperature: 100° C is hardly twice 50° C".\textemdash E. Bidwell Wilson.

"Mathematics is a natural science ... it has its origin in the objective world, of which it studies the spatial and numerical aspects. The law that $2 \times 2 = 4$ is not only a law on paper, but as a mathematical law expresses relations in objective reality, like the law that hydrogen and oxygen form water under proper conditions".\textemdash D. J. Struik.

\textsuperscript{71} Lillie, R., Science, 46, 139 (1927).
\textsuperscript{72} Russell, Bertrand, "What I believe," Nation, p. 412, 1940.
“One cannot escape the feeling that mathematical formulas have an independent existence and an intelligence of their own... that we get more out of them than was originally put into them.”—Heinrich Hertz.

“One tries... to employ numerical discourse... because of the stock of ready-made devices and calculations which were accumulated in the pursuit of mathematics”.—Leonard Bloomfield.

For our purposes, the usefulness of mathematics consists in its operational convenience. Mathematics is a lever, as it were, by the use of which unwieldy masses of experimental data are lifted into analytic view. The tremendous progress of the physical sciences in general and of engineering in particular since the Renaissance is in large measure due to applications of the analytic mathematical methods developed during this period. These methods should also prove fruitful in the investigation of motions of biological phenomena, such as growth.

The operational advantages and disadvantages of mathematics are not unlike those of symbolic logic73. Both have the advantages of simplicity, “purity”, and isolation. But the advantages of generality, simplicity, purity, and isolation are also disadvantages. A symbolic language isolated from the material world cannot fully represent the complex phenomenal interrelationship of the material world, although it is probable, as indicated, for example, by the groupings of matrix algebra, that the symbolic language of mathematics and logic will develop a broader adequacy reflecting physical reality to a greater extent. Regardless, therefore, of the technical refinements of a mathematical result, its representation of a situation is necessarily inadequate and over-simplified, and must be interpreted in the light of what is called “common sense”, that is, judgment in the light of experience.

In connection with the widespread application of the mechanical rules of statistics to biology, Wilson74 writes: “I say beware of the mere formal application of probable error to meager statistical material. Your conclusions will almost certainly be wrong. The statistical method, like other methods, is not a substitute for, but a humble aid to the formation of a scientific judgment. Only with this philosophy in mind may we truly hope, with care, to avoid in the main being classed in the superlative category of that oft-cited sequence of liars, damned liars, and statisticians!”

Sets of observations, for example, basal metabolism and body weight (Chs. 13 to 15), are usually related to each other by some equation. The equation may be empirical or rational. There are many degrees of rationality, but the constants of the rational equation should at least have definiteness of meaning. A potential series, such as \( Y = a + bX + cX^2 + dX^3 \ldots \), is not rational because (1) any continuous set of observations can be represented by such a series if enough terms are chosen, and (2) if one of the terms of the series is omitted, the remaining constants assume different numerical values. This type of equation is, therefore, ambiguous because its terms have no definite, constant, meaning.

An empiric equation, then, may have description value, but does not represent a uniformity of nature. A rational equation, such as the gas law \( PV = NRT \), or the gravitational equation \( F = G(MM'/d^2) \), represents a certain concept of the phenomenon, perhaps idealized, that is, undisturbed by lesser causes, the constants of which are unambiguously defined. Rational equations often represent the data with less precision than empiric, because of their idealization. On the other hand, a prediction based on a rational equation is more reliable. The distinguishing feature of the rational equation

74 Wilson, E. Bidwell, Science, 80, 193 (1934); 58, 93 (1923); 63, 289 (1926); 65, 581 (1927).
is not that it represents data with great precision, but that it represents or intends to represent a uniformity or "law" of nature.

Equations frequently have broader significance than the author believes them to have, so that they can represent with equal facility quite different, even contradictory, theories. Likewise, different types of equations may often represent the same phenomenon. There is, therefore, no dividing line between rational and empiric equations except in the author's concept.

In the last analysis, mathematical representations are oversimplified mathematical models, only partial descriptions of a limited portion of a long chain of interrelated events, rather than explanations. This is due to the discrepancy between the necessarily idealized nature of the assumptions for mathematical representation on the one hand and the complexity of the "field" or the process on the other. A mathematical equation represents an isolated relationship while reality is organismic, with complex multi-dimensional ramifications. Rationalism and empiricism are, therefore, relative terms, descriptive of the spirit of the investigator.

Empiric equations are useful for condensing unwieldy tables into a brief formula, for codification (e.g., formulating growth standards), classifications (e.g., with regard to rate of growth and development, variability, correlation, etc.), but not for predicting outside the observed limits. Agriculturists are familiar with the practical usefulness of age and other time "standards" of physical growth, milk production, egg production, wool production, fertility, life expectancy, and so on.

10.11: Summary. This chapter is concerned with a very general principle in biology, designated "homeostasis" by Cannon, which may be called the principle of Claude Bernard for living systems analogous to the principle of Le Chatelier for non-living systems.

Homeostasis, or the principle of Claude Bernard, refers to the regulatory mechanisms which maintain constant the "internal environment" of the organism in the face of changing conditions. Thus the body temperature of man remains constant although the external environmental temperature may range from 0°F to 100°F; high-milking dairy cows gain (from the feed) or lose (into the milk) colossal amounts of minerals, proteins, carbohydrates, and water, yet maintain constant the concentration of these nutrients in the blood; and so on.

Homeostasis is the major manifestation of what is sometimes referred to as the "field" formulated by the "organismic theory" in biology. "Field" refers to the totality of the interactions in the living system with the environment, internal and external. The living field pattern of the biologist is analogous to the electromagnetic field pattern of the physicist. The behavior of the bodily constituents is determined by the living field structure as a whole in the same sense as the behavior of iron filings or of electric events is determined by the electromagnetic field structure as a whole. This living field pattern has a certain dynamic stability, that is, it tends to restore itself to "normal" by many organismic or homeostatic devices.

These concepts of field, organism, and especially homeostasis, were extended to societies of organisms, especially to their ever finer social integration in the course of evolution; and to certain philosophic aspects in sociology and social
evolution. Human society is apparently in the throes of a transition period due to the unbalanced development of techniques, discussed in the text (also in Ch. 25).

The concepts of field and homeostasis invalidate the concept of “cause” as a one-sided action. Thus many endocrines are stimulated to activity by the pituitary (tropic hormones). But this is not one-sided; the glands which are controlled by the pituitary also control the pituitary. The interrelation is mutual. Moreover, the pituitary is, itself, a part of the total functioning organism, and can function only as the organism keeps it so. Similarly in other realms: high government expenses “cause” high taxes; and high taxes “cause” high government expenses. The interrelation is mutual.

The field concepts of living and non-living systems may be integrated into a more general field concept. There is no sharp dividing line between living and non-living, but they function at different levels, just as within the living category, there are many different levels of organization and function.

The narrow border between living and non-living, at its limit, is indicated by the fact that crystalline protein (“non-living”) prepared from tobacco-mosaic virus has the ability to propagate itself (“living”). The bacteriophage is in the same category.

During growth and development the “field” is thought of as an integrative process which organizes the diverse elements into an integrated unit. The structure has many categories—atoms, ions, molecules, cells, organs, organ systems; but these structures, at different levels of complexity, function together harmoniously as part of the “field”. The living field is stable, yet its stability is not static but dynamic. Thus protoplasm is chemically very unstable, but an organism like a man may function in the same recognizable individual form for a century. The individual atoms and molecules are undergoing continuous change, but the pattern, the “field”, remains until a limiting homeostatic mechanism breaks down and the organism dies.

The principle of homeostasis is illustrated in the text by many examples, earthy and theoretical. Indeed every chapter in this book is an illustration of this principle. It is an extremely useful one in biology; like the theory of evolution, it binds scattered facts, apparently unrelated and confusing, into a sane whole.

General comments are presented on the use of mathematics in biology, with special reference to the relative significance of rational and empirical equations.
