Closed and Open Systems

W. Koehler

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[. . .] As it becomes more and more apparent that the machine principle is not capable of giving us a satisfactory explanation of organic regulation, an interpretation in more functional or dynamic terms began to attract some theorists. At first it seems indeed a plausible assumption that in the organism fitting regulation toward a standard status occurs for the same reasons that make physical systems attain or re-establish an equilibrium. Unfortunately, however, the concept of "equilibrium" is in this connexion often used in just as vague a meaning as had previously been the case with the concept "machine". It appeared therefore advisable to analyse physical regulation before a comparison was undertaken between the normal state of an organism and an equilibrium in physics.

On the face of it, these standard states seem to resemble each other in a most promising manner. There is besides a special point which gives an equilibrium theory of organic regulation a particularly inviting appearance. Physical systems, we have found, tend to transform themselves in the direction of an equilibrium for two reasons: either because their processes follow the second law of thermodynamics, or because the law of dynamic direction applies to them. Now, even the most superficial consideration of the organism must convince everybody that its normal state cannot be a mere thermodynamic equilibrium. If, therefore, an equilibrium theory of organic regulation is to be at all proposed, this can be done only with the premise that both the law of dynamic direction and the second law apply to the organism; in other words, that the organism regulates toward a balance of directed vectors no less than it does toward "a most probable situation". We have seen, however, that the law of dynamic direction does not determine what actually happens in a system, unless there is sufficient friction by which inert macroscopic velocities are eliminated. Is this condition fulfilled in an organism? Without any doubt it is. In the movements of our limbs and in circulation inert velocities may perhaps play a modest role. In the tissue, however, friction is as great as it is in the interior of any solution. Consequently there are no such velocities in the tissue. What happens here must, from the point of view of physics, follow either from the second law or from the law of dynamic direction. In the former case we could say with the physicists that changes will occur in the direction of "higher probabilities"; in the second case, the displacements will be proportional to, and in the direction of, the vectors which happen to obtain at each point.

The fact that the organism contains many "devices", i.e. relatively permanent conditions of function, implies no obstacle for an equilibrium theory of organic regulation. In a physical system there may be many constraints; and yet, within the limitations which are thus imposed upon its operations, the tendency toward an equilibrium will determine what actually happens. We have only to realize that the equilibrium in question will itself respect those limiting constraints. In this sense the principal idea of all machine theories is entirely compatible with the more dynamic or functional notions to which an equilibrium theory refers.

On the other hand, it is the existence of relatively rigid anatomical conditions which restricts the range of possible organic regulations. Such devices as the organism possesses are undoubtedly apt to give the tendency toward standard states a general direction which is particularly fitting under more or less normal conditions. At the same time they exclude, precisely among the higher vertebrates, some regulations which might otherwise occur even in quite *un*usual situations. Such anatomical facts are, as it were, "not made for these conditions"; and since they do not yield to the stress of altered function they prevent, under these circumstances, the actual occurrence of complete regulation.

So far, then, an equilibrium theory of regulation may seem to be wholly compatible with what we know about the organism. Any interpretation of organic fitness that does not take account of our two functional principles appears to me indeed as fundamentally unsound. On the other hand, it is equally true that neither the second law nor the law of dynamic direction can be applied to the organism in that simplest formulation in which they refer to equilibria. I have been at some pains to make the meaning of these principles more explicit than is often done, because I wish it to be perfectly clear that, unless a much broader view be taken, an equilibrium theory of organic regulation would be entirely misleading. To express the main argument against such a theory quite briefly: neither is the standard state of an organism a state of equilibrium in the common sense of the word, nor do organic processes in their totality generally tend to approach such an equilibrium.

In the introductory chapter of his book Cannon (1932) remarks that "the constant conditions which are maintained in the body might be termed *equilibria*". The author does not say what relation he assumes to obtain between this functional principle and his own view according to which regulation seems always to be due to regulating devices. At any rate, he prefers to give the name *homeostasis* to the fact that certain "steady states" are so obstinately preserved or re-established in the organism. Equilibria, he adds, are found in simple closed systems, "where known forces are balanced". Again, he says, the word homeostasis "does not imply something set and immobile, a stagnation". There is something in these last words which many biologists may appreciate when attempts are made to explain organic regulation by an "equilibrium theory".

Convincing objections may, in fact, be raised against any such attempts. First, as Cannon says, no organism is detached from the rest of the world to an extent that would make our principles directly applicable to living systems. These systems are not closed. They absorb and they emit energy. At times they absorb much more than they emit. From the point of view of physics it is, therefore, simply impossible to state it as a rule that transformations in organisms occur in the direction of equilibria.

The same follows from the fact that in a healthy normal condition many vertebrates are by no means in equilibrium with regard to their immediate environment. Mammals, for instance, *stand* when at rest; for the most part they lie down only when slightly or seriously fatigued. Many fishes assume when at rest a position in which their heavier parts are turned away from the direction of gravitation. And yet in a state of physical equilibrium the center of gravity both of mammals and of fishes should be lowered as far as possible. Since no outer physical forces keep the mammals standing and the fishes swimming against the pull of gravitation, i.e. in an unstable position, such organisms must, when fresh, healthy, and therefore in their standard state, contain sets of vectors and processes which *prevent* the attainment of an equilibrium. These factors represent a certain amount of potential energy. But no physical system that is as such in a state of equilibrium can at the same time preserve an energy reserve by which it avoids reaching an equilibrium with regard to the environment. In the present example those factors seem even to keep the organism in a state *that departs from an equilibrium as much as possible*.

No conclusion other than this can be drawn from what happens during the development of individual organisms. During youth the standard state, for instance of man, varies slowly with time. There is always regulation toward a state that may be called temporarily normal. But from month to month, and from year to year, this state shifts gradually; and it is obvious that regulation changes its "goal" correspondingly. Thus, if we know in what direction the standard state of the full-grown healthy adult differs from that of the healthy child, we shall also be enabled to define in what direction, toward what kind of state, regulation occurs when the individual is fully developed. We see the answer at once. In a state of equilibrium, as defined in this chapter, a system contains the smallest amount of potential energy, however, is the capacity of a system for macroscopic activities. Nobody, I am sure, will contend that a man of thirty can do less macroscopic work than can the new-born child. Just the contrary is true. From the point of view of physics the adult contains tremendous stores of potential energy when compared with the child. It follows that, in the healthy individual, development toward adult life is associated with an *increase* of such energy, that accordingly during this period regulation occurs in the direction of ever higher levels, and that, when development is at its peak, it is a *maximum*, not a minimum, of available energy which regulation tends to preserve.

These arguments must, I believe, convince everybody that an "equilibrium theory" of organic homeostasis is not compatible with elementary biological facts. What is the theorist to do in this situation? In Professor a. V. Hill's words (1931, p. 60): "*If there be no equilibrium, how far dare we apply rules and formulae derived from the idea of equilibrium?*" In several statements the same author hints at a possible answer. All physiologists, he says, "must have exercised their minds as to the reason why a living cell, completely at rest, and doing nothing at all except maintain its continued existence, requires a continual supply of energy" (Hill, 1931, p. 4). For instance, "apart from any motor activity at all, a human muscle cell . . . uses, to maintain itself alone, about 30 calories of energy per gramme per day" (Hill, 1931, p. 60). We are, he finds, thus forced to adopt "the conception of a dynamic steady state maintained by a continual expenditure of energy" (Hill, 1931, p. 62).

I should like to add that there is nothing hazardous in this conception. We can easily give it a clear functional meaning if we consider one more physical example. Life has sometimes been compared to a flame (e.g. Roux, 1914, p. 17, p. 79). This is more than a poetical metaphor, since, from the point of view of function and energetic, life and a flame have actually much in common. The flame, say, of a candle is a steady state. The continued existence of this state involves a continual supply of potential energy which the flame receives as "food" through the wick and as oxygen from the air.[1] When undisturbed, the flame remains the same in size and in shape. Thus one might be tempted to believe that its status is that of an equilibrium. In order to see this we need only apply the same test to which we just subjected the adult organism: what is the genesis of a flame? We light a candle with a match. On the wick there appears at first a tiny flame. This flame grows spontaneously until it attains a maximum size and at the same time a certain shape, which then remain unaltered. If during the initial phase we hold our hand near the flame we can easily feel that quickly *increasing* amounts of heat are emitted at this time. We also see that during this period the flame throws more and more light on its environment. Any energy, however, which the flame emits at a given moment was just before this moment inner energy of the flame itself; again, a moment before, it was potential (chemical) energy that was ready to be transformed into heat and light. From our simple observation it follows, therefore, that during its "youth" the flame attains ever higher degrees of potential energy and that in its final stationary state it contains a maximum of such energy. In this sense the steady state of the flame departs as widely from a condition of equilibrium as it possibly can.

The factors which determine the maximum energy of the flame may be indicated in a few words. As soon as the candle is lighted, "food" which is contained in the wick and oxygen that is contained in the air are being spent by combustion. Thus gradients are set up both for the food and for the oxygen. The flame begins to grow, and these gradients increase correspondingly. Higher amounts are therefore supplied both of food and of oxygen. But there is a limit to this process. When a certain size and a certain maximum of combustion have been reached, any further growth of the flame would lead to a higher demand than is compatible with the possible speed of oxygen diffusion from the surrounding air and with that of the food-stream which passes through the wick.

We are now in a position to apply our theoretical concepts to the flame and then to the organism. The flame is not a closed system. It can, however, be considered as part of a larger system for which our general principles are valid. If this be done certain consequences will follow for the behaviour of the flame as such. The air of the environment and the substance of the candle, taken together, contain amounts of chemical energy which are to all practical purposes unlimited. If therefore the material of the candle and a sufficiently large volume of air are included, we obtain a "system" which we may regard as closed; because during the lifetime of the flame the energy on which its steady state depends will be exclusively supplied by the candle and this volume of air. An untrained observer's attention may be completely concentrated on the flame as an outstanding visual fact. From a functional point of view, however, the life of the flame can be understood only in the context of that larger "system". This system follows our general laws. The changes which occur in it must as a while have a direction which lowers the amount of potential energy contained in the system. So long as the candle is not lighted this chemical energy cannot be spent at all. On the other hand, once a sufficiently high temperature is created a the tip of the wick, energy begins to be spent by combustion. And the more the flame grows, the more energy will be expended per unit of time.

It comes then to this: our system consists of, first, a practically unlimited store of chemical energy which, however, cannot be directly spent; and, secondly of a minor part, the flame, in which this energy *can* be spent up to a certain maximum rate. The "system" as a whole will lose its potential energy the more quickly, the more of this energy streams into the only part of it in which it can be expended. This is the flame. For this reason a maximum of such energy migrates steadily into the flame; for the same reason the flame *contains* continually a maximum of potential energy. Only thus is it enabled to expend energy at a maximum rate.

The fact that the stationary state of the minor system involves a maximum of potential energy is entirely compatible with our general principles. These refer to closed systems; and in the closed system of the present example, taken as a whole, events have precisely the direction which is prescribed by those principles. On the other hand, it is obviously an essential observation that in the only "working" part of this closed system the direction of events is just the opposite of that to which the principles refer. The activity of the flame as such, it is true, namely combustion, tends to lower the amount of potential energy in the flame. But this does not really happen because any spent energy is at once replaced by a corresponding new supply. The more energy the flame emits, the higher is the rate at which it is supplied. Thus the flame is continuously fed with the greatest possible amount of energy.

A general view of the organism shows us a situation which resembles strongly that of the flame. The organism is not a closed system; it is part of a larger functional context, the external section of which contains as its most important components oxygen and food, i.e. a store of chemical energy which may be regarded as practically unlimited. In one respect there is a difference between the flame and the organism: unlike the flame, the organism itself normally contains great reserves of food in the widest sense of the word; it is stored, for instance, in the liver. From these sources rather than from the outside other tissues receive their food supply directly.

The potential energy of oxygen and food is not spontaneously spent outside the organism; nor is the food reserve consumed where it is stored within the organism. All "activities", however, of which the organism is capable do tend to lower the supply of chemical energy that is contained in the active tissues. This is in line with our principles. But it is also in line with these principles that under such circumstances the stores of food deliver new supplies, and that these tend to maintain or to re-establish the highest energetic level of the tissues. If we compare this situation with that obtaining in a flame, we shall expect the active organism to heighten its content of potential energy during youth, and to preserve this content when a maximum is reached. This exactly the behavior of the organism to which I pointed when I showed that the standard state of the organism cannot be a state of equilibrium.

Suppose now that at a given time there exists in the organism only one state of the tissue which corresponds to a maximum of potential energy. If by considerable work or by any other influence an organ or some larger part is changed so that for the organism as a whole the maximum condition is no longer maintained, such processes will occur as will bring it back to higher levels of energy. And since there is only one standard state in which a further increase is not possible, the organism will from various initial states "regulate" toward that maximum condition. In other words, so far as regulation is concerned, our previous discussion of standard states applies to a maximum condition, just as it did to an equilibrium. Of course, it applies quite generally. There will, for instance, be in this case the same influence of given anatomical constraints as was mentioned in the case of regulation toward an equilibrium. Again, regulation toward a highest standard state will only be possible within limits which are given by relatively unalterable anatomical facts.

Actual regulation, however, will now be characterized by one remarkable trait. On the highest possible level of potential energy a system is capable of doing more macroscopic work than it is on any other level. If, therefore, in the organism any change by which this level is lowered tends to be followed by processes which counteract that change, and thus re-establish the highest level, regulation will serve to keep the living system in its most powerful state and, in this sense, to protect it. This, it seems, is the condition in which the various tissues are maintained by a constant supply of energy and which is so often spontaneously restored after disturbances.[2]

I realize that in the last paragraphs no more than a general outline has been given, which cannot become a theory until a great many biological facts have been considered from this point of view. Since this task does not belong to our present program I shall only add a few tentative remarks.

One might ask why with these premises an organism does not live forever. My answer would be that regulation has its limits for reasons which I mentioned before; and that, therefore, a great many influences are able to destroy life. It is quite as obvious that without a sufficient supply of food and of oxygen the level of life will soon sink. For the same reason organisms can die from exhaustion, but they seem also to deteriorate spontaneously when a critical age has been passed. It appears to me quite likely that practically all our activities tend slightly to alter the tissue in a way which does not at once disturb further function, but which cannot be fully compensated for by the metabolism and its regulatory tendency. If such changes accumulate for years they may gradually make the tissue or certain organs less fit to respire and to absorb food. What this would mean is fairly obvious.

A further question refers to the manner in which the organism obtains its food. So long as within the organism there are reserves of carbohydrates, fats, and so forth, the situation seems simple enough. But these reserves are limited, and I want to make it quite clear that the way in which the organism replenishes its stores is something altogether different from the simple processes that feed a flame with chemical energy. Delivery of both food and oxygen is in the case of the flame entirely automatic and direct. The existence of the flame sets up gradients in both respects, and those materials move in the direction of the gradients. Not much oxygen penetrates in this simple manner into the interior of a bird or a mammal; nor does food migrate into our interior simply because we are spending energy there. In the case of food, for instance, what happens is more complicated: among our activities there is one group, that of finding and of eating food, in which we *expend* certain amounts of energy, just as we do in all the others. As a result of these activities, however, we *absorb* under favorable conditions much more potential energy than is spent in order to obtain it. Thus the organism stores new supplies which enable it to maintain its raised normal level and, besides, to be active in other directions. In this there is nothing that could unbalance the energy budget; there is no contradiction between such operations and our general principles. None the less it must be noted that this particular behavior cannot be *predicted* from such principles, and that, from a general functional standpoint, it is a remarkable trait of living systems, about as remarkable as their reproductive activities. An actual theory of the organism will, if I am not mistaken, meet its most fascinating problems here.

There is not apparent reason, however, why science should hesitate to deal with the problem of *regulation*. Nor is there any essential difficulty in the fact that organic regulation is generally directed toward an "optimum" state. The physicists, it is true, have not given much attention to this functional possibility, although it follows from their general laws. Also, a thorough investigation of *heterogeneous* physical systems and of their regulatory behavior would contribute greatly to a further understanding of organic fitness. But even now we can predict from known principles that some such systems will show an impressive casual harmony by which they themselves keep in a "healthy" condition, as though this were their goal.

It is perhaps too early for final statements in this field, particularly since we know so little about the way in which evolution has created the living world. As this world now is, however, the following seems to me a conservative description of the situation: no procedure of science reveals any actual participation of demands and values in the determination of organic events. At the same time, science can clearly demonstrate that in certain systems function will, for dynamic reasons, take a most "fitting" course. We do not discover requiredness as such among the data of science. But a general trend of nature is sometimes found to yield the same results as might be expected if the events in question were actually happening in order to fulfill a demand.

REFERENCES

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[1] Chemical energy is often treated in such cases as a form of potential energy. In fact, in all respects which concern us here it *is* potential energy.

[2] I have sometimes been asked why I refuse to call the standard state of the organism "an equilibrium". My reason is simply that this standard state is not an equilibrium in any sense which has as yet been defined by science - not even an *un*stable equilibrium. It is a *stationary process*; and we are just beginning to learn that there are two classes of stationary processes, one with which a minimum, and another with which a maximum of energy is associated. Nothing could be more unfortunate than an attempt to hide such new essential distincitions behind an outworn general term.