Life's Irreducible Structure

Live mechanisms and information in DNA are boundary conditions with a sequence of boundaries above them.

Michael Polanyi

If all men were exterminated, this would not affect the laws of inanimate nature. But the production of machines would stop, and not until men arose again could machines be formed once more. Some animals can produce tools, but only men can construct machines; machines are human artifacts, made of inanimate material.

The *Oxford Dictionary* describes a machine as "an apparatus for applying mechanical power, consisting of a number of interrelated parts, each having a definite function." It might be, for example, a machine for sewing or printing. Let us assume that the power driving the machine is built in, and disregard the fact that it has to be renewed from time to time. We can say, then, that the manufacture of a machine consists in cutting suitably shaped parts and fitting them together so that their joint mechanical action should serve a possible human purpose.

The structure of machines and the working of their structure are thus shaped by man, even while their material and the forces that operate them obey the laws of inanimate nature. In constructing a machine and supplying it with power, we harness the laws of nature at work in its material and in its driving force and make them serve our purpose.

This harness is not unbreakable; the structure of the machine, and thus its working, can break down. But this will not affect the forces of inanimate nature on which the operation of the machine relied; it merely releases them from the restriction the machine imposed on them before it broke down.

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So the machine as a whole works under the control of two distinct principles. The higher one is the principle of the machine's design, and this harnesses the lower one, which consists in the physical-chemical processes on which the machine relies. We commonly form such a two-leveled structure in conducting an experiment; but there is a difference between constructing a machine and rigging up an experiment. The experimenter imposes restrictions on nature in order to observe its behavior under these restrictions, while the constructor of a machine restricts nature in order to harness its workings. But we may borrow a term from physics and describe both these useful restrictions of nature as the imposing of *boundary conditions* on the laws of physics and chemistry.

Let me enlarge on this. I have exemplified two types of boundaries. In the machine our principal interest lay in the effects of the boundary conditions, while in an experimental setting we are interested in the natural processes controlled by the boundaries. There are many common examples of both types of boundaries. When a saucepan bounds a soup that we are cooking, we are interested in the soup; and, likewise, when we observe a reaction in a test tube, we are studying the reaction, not the test tube. The reverse is true for a game of chess. The strategy of the player imposes boundaries on the several moves, which follow the laws of chess, but our interest lies in the boundaries—that is, in the strategy, not in the several moves as exemplifications of the laws. And similarly, when a sculptor shapes a stone or a painter composes a painting, our interest lies in the boundaries imposed on a material, and not in the material itself.

We can distinguish these two types of boundaries by saying that the first represents a test-tube type of boundary whereas the second is of the machine type. By shifting our attention, we may sometimes change a boundary from one type to another.

All communications form a machine type of boundary, and these boundaries form a whole hierarchy of consecutive levels of action. A vocabulary sets boundary conditions on the utterance of the spoken voice; a grammar harnesses words to form sentences, and the sentences are shaped into a text which conveys a communication. At all these stages we are interested in the boundaries imposed by a comprehensive restrictive power, rather than in the principles harnessed by them.

Living Mechanisms Are Classed with Machines

From machines we pass to living beings, by remembering that animals move about mechanically and that they have internal organs which perform functions as parts of a machine do—functions which sustain the life of the organism, much as the proper functioning of parts of a machine keeps the machine going. For centuries past, the workings of life have been likened to the working of machines and physiology has been seeking to interpret the organism as a complex network of mechanisms. Organs are, accordingly, defined by their life-preserving functions.

Any coherent part of the organism is indeed puzzling to physiology—and also meaningless to pathology—until the way it benefits the organism is discovered. And I may add that any description of such a system in terms of its physical-chemical topography is meaningless, except for the fact that the description covertly may recall the system's physiological interpretation—much as the topography of a machine is meaningless until we guess how the device works, and for what purpose.

In this light the organism is shown to be, like a machine, a system which works according to two different principles: its structure serves as a boundary condition harnessing the physical-chemical processes by which its organs perform their functions. Thus, this system may be called a system under dual control. Morphogenesis, the process by which the structure of living beings develops, can then be likened to the shaping of a machine which will act as a boundary for the laws of inanimate nature. For just as these laws serve the machine, so they serve also the developed organism.

A boundary condition is always extraneous to the process which it delimits. In Galileo's experiments on balls rolling down a slope, the angle of the slope was not derived from the laws of mechanics, but was chosen by Galileo. And as this choice of slopes was extraneous to the laws of mechanics, so is the shape and manufacture of test tubes extraneous to the laws of chemistry.

The same thing holds for machinelike boundaries; their structure cannot be defined in terms of the laws which they harness. Nor can a vocabulary determine the content of a text, and so on. Therefore, if the structure of living things is a set of boundary conditions, this structure is extraneous to the laws of physics and chemistry which the organism is harnessing. Thus the morphology of living things transcends the laws of physics and chemistry.

DNA Information Generates Mechanisms

But the analogy between machine components and live functioning organs is weakened by the fact that the organs are not shaped artificially as the parts of a machine are. It is an advantage, therefore, to find that the morphogenetic process is explained in principle by the transmission of information stored in DNA, interpreted in this sense by Watson and Crick.

A DNA molecule is said to represent a code—that is, a linear sequence of items, the arrangement of which is the information conveyed by the code. In the case of DNA, each item of the series consists of one out of four alternative organic bases (*1*). Such a code will convey the maximum amount of information if the four organic bases have equal probability of forming any particular item of the series. Any difference in the binding of the four alternative bases, whether at the same point of the series or between two points of the series, will cause the information conveyed by the series to fall below the ideal maximum. The information content of DNA is in fact known to be reduced to some extent by redundancy, but I accept here the assumption of Watson and Crick that this redundancy does not prevent DNA from effectively functioning as a code. I accordingly disregard, for the sake of brevity, the redundancy in the DNA code and talk of it as if it were functioning optimally, with all of its alternative basic bindings having the same probability of occurrence.

Let us be clear what would happen in the opposite case. Suppose that the actual structure of a DNA molecule were due to the fact that the bindings of its bases were much stronger than the bindings would be for any other distribution of bases, then such a DNA molecule would have no information content. Its codelike character would be effaced by an overwhelming redundancy.

We may note that such is actually the case for an ordinary chemical molecule. Since its orderly structure is due to a maximum of stability, corresponding to a minimum of potential energy, its orderliness lacks the capacity to function as a code. The pattern of atoms forming a crystal is another instance of complex order without appreciable information content.

There is a kind of stability which often opposes the stabilizing force of a potential energy. When a liquid evaporates, this can be understood as the increase of entropy accompanying the dispersion of its particles. One takes this dispersive tendency into account by adding its powers to those of potential energy, but the correction is negligible for cases of deep drops in potential energy or for low temperatures, or for both. We can disregard it, to simplify matters, and say that chemical structures established by the stabilizing powers of chemical bonding have no appreciable information content.

In the light of the current theory of evolution, the codelike structure of DNA must be assumed to have come about by a sequence of chance variations established by natural selection. But this evolutionary aspect is irrelevant here; whatever may be the origin of a DNA configuration, it can function as a code only if its order is not due to the forces of potential energy. It must be as physically indeterminate as the sequence of words is on a printed page. As the arrangement of a printed page is extraneous to the chemistry of the printed page, so is the base sequence in a DNA molecule extraneous to the chemical forces at work in the DNA molecule. It is this physical indeterminacy of the sequence that produces the improbability of occurrence of any particular sequence and thereby enables it to have a meaning—a meaning that has a mathematically determinate information content equal to the numerical improbability of the arrangement.

DNA Acts as a Blueprint

But there remains a fundamental point to be considered. A printed page may be a mere jumble of words, and it has then no information content. So the improbability count gives the *possible*, rather than the *actual*, information content of a page. And this applies also to the information content attributed to a DNA molecule; the sequence of the bases is deemed meaningful only because we assume with Watson and Crick that this arrangement generates the structure of the offspring by endowing it with its own information content.

This brings us at last to the point that I aimed at when I undertook to analyze the information content of DNA: Can the control of morphogenesis by DNA be likened to the designing and shaping of a machine by the engineer? We have seen that physiology interprets the organism as a complex network of mechanisms, and that an organism is—like a machine—a system under dual control. Its structure is that of a boundary condition harnessing the physical-chemical substances within the organism in the service of physiological functions. Thus, in generating an organism, DNA initiates and controls the growth of a mechanism that will work as a boundary condition within a system under dual control.

And I may add that DNA itself is such a system, since every system conveying information is under dual control, for every such system restricts and orders, in the service of conveying its information, extensive resources of particulars that would otherwise be left at random, and thereby acts as a boundary condition. In the case of DNA this boundary condition is a blueprint of the growing organism (*2*).

We can conclude that in each embryonic cell there is present the duplicate of a DNA molecule having a linear arrangement of its bases—an arrangement which, being independent of the chemical forces within the DNA molecules, conveys a rich amount of meaningful information. And we see that when this information is shaping the growing embryo, it produces in it boundary conditions which, themselves being independent of the physical chemical forces in which they are rooted, control the mechanism of life in the developed organism.

To elucidate this transmission is a major task of biologists today, to which I shall return.

Some Accessory Problems Arise Here

We have seen boundary conditions introducing principles not capable of formulation in terms of physics or chemistry into inanimate artifacts and living things; we have seen them as necessary to an information content in a printed page or in DNA, and as introducing mechanical principles into machines as well as into the mechanisms of life.

Let me add now that boundary conditions of inanimate systems established by the history of the universe are found in the domains of geology, geography, and astronomy, but that these do not form systems of dual control. They resemble in this respect the test-tube type of boundaries of which I spoke above. Hence the existence of dual control in machines and living mechanisms represents a discontinuity between machines and living things on the one hand and inanimate nature on the other hand, so that both machines and living mechanisms are irreducible to the laws of physics and chemistry.

Irreducibility must not be identified with the mere fact that the joining of parts may produce features which are not observed in the separate parts. The sun is a sphere, and its parts are not spheres, nor does the law of gravitation speak of spheres; but mutual gravitational interaction causes the parts of the sun to form a sphere. Such cases of holism are common in physics and chemistry. They are often said to represent a transition to living things, but this is not the case, for they are reducible to the laws of inanimate matter, while living things are not.

But there does exist a rather different continuity between life and inanimate nature. For the beginnings of life do not sharply differ from their purely physical-chemical antecedents. One can reconcile this continuity with the irreducibility of living things by recalling the analogous case of inanimate artifacts. Take the irreducibility of machines; no animal can produce a machine, but some animals can make primitive tools, and their use of these tools may be hardly distinguishable from the mere use of the animal's limbs. Or take a set of sounds conveying information; the set of sounds can be so obscured by noise that its presence is no longer clearly identifiable. We can say, then, that the control exercised by the boundary conditions of a system can be reduced gradually to a vanishing point. The fact that the effect of a higher principle over a system under dual control can have any value down to zero may allow us also to conceive of the continuous emergence of irreducible principles within the origin of life.

We Can Now Recognize Additional Irreducible Principles

The irreducibility of machines and printed communications teaches us, also, that the control of a system by irreducible boundary conditions does not *interfere* with the laws of physics and chemistry. A system under dual control relies, in fact, for the operations of its higher principle, on the working of principles of a lower level, such as the laws of physics and chemistry. Irreducible higher principles are *additional* to the laws of physics and chemistry. The principles of mechanical engineering and of communication of information, and the equivalent biological principles, are all additional to the laws of physics and chemistry.

But to assign the rise of such additional controlling principles to a selective process of evolution leaves serious difficulties. The production of boundary conditions in the growing fetus by transmitting to it the information contained in DNA presents a problem. Growth of a blueprint into the complex machinery that it describes seems to require a system of causes not specifiable in terms of physics and chemistry, such causes being additional both to the boundary conditions of DNA and to the morphological structure brought about by DNA.

This missing principle which builds a bodily structure on the lines of an instruction given by DNA may be exemplified by the far-reaching regenerative powers of the embryonic sea urchin, discovered by Driesch, and by Paul Weiss's discovery that completely dispersed embryonic cells will grow, when lumped together, into a fragment of the organ from which they were isolated (*3*). We see an integrative power at work here, characterized by Spemann and by Paul Weiss as a "field" (*4*), which guides the growth of embryonic fragments to form the morphological features to which they embryologically belong. These guides of morphogenesis are given a formal expression in Waddington's "epigenetic landscapes" (*5*). They say graphically that the growth of the embryo is controlled by the gradient of potential shapes, much as the motion of a heavy body is controlled by the gradient of potential energy.

Remember how Driesch and his supporters fought for recognition that life transcends physics and chemistry, by arguing that the powers of regeneration in the sea urchin embryo were not explicable by a machinelike structure, and how the controversy has continued, along similar lines, between those who insisted that regulative ("equipotential" or "organismic") integration was irreducible to any machinelike mechanism and was therefore irreducible also to the laws of inanimate nature. Now if, as I claim, machines and mechanical processes in living beings are themselves irreducible to physics and chemistry, the situation is changed. If mechanistic and organismic explanations are both equally irreducible to physics and chemistry, the recognition of organismic processes no longer bears the burden of standing alone as evidence for the irreducibility of living things. Once the "field"-like powers guiding regeneration and morphogenesis can be recognized without involving this major issue, I think the evidence for them will be found to be convincing.

There is evidence of irreducible principles, additional to those of morphological mechanisms, in the sentience that we ourselves experience and that we observe indirectly in higher animals. Most biologists set aside these matters as unprofitable considerations. But again, once it is recognized, on other grounds, that life transcends physics and chemistry, there is no reason for suspending recognition of the obvious fact that consciousness is a principle that fundamentally transcends not only physics and chemistry but also the mechanistic principles of living beings.

Biological Hierarchies Consist of a Series of Boundary Conditions

The theory of boundary conditions recognizes the higher levels of life as forming a hierarchy, each level of which relies for its workings on the principles of the levels below it, even while it itself is irreducible to these lower principles. I shall illustrate the structure of such a hierarchy by showing the way five levels make up a spoken literary composition.

The lowest level is the production of a voice; the second, the utterance of words; the third, the joining of words to make sentences; the fourth, the working of sentences into a style; the fifth, and highest, the composition of the text.

The principles of each level operate under the control of the next-higher level. The voice you produce is shaped into words by a vocabulary; a given vocabulary is shaped into sentences in accordance with a grammar; and the sentences are fitted into a style, which in turn is made to convey the ideas of the composition. Thus each level is subject to dual control: (i) control in accordance with the laws that apply to its elements in themselves, and (ii) control in accordance with the laws of the powers that control the comprehensive entity formed by these elements.

Such multiple control is made possible by the fact that the principles governing the isolated particulars of a lower level leave indeterminate conditions to be controlled by a higher principle. Voice production leaves largely open the combination of sounds into words, which is controlled by a vocabulary. Next, a vocabulary leaves largely open the combination of words to form sentences, which is controlled by grammar, and so on. Consequently, the operations of a higher level cannot be accounted for by the laws governing its particulars on the next-lower level. You cannot derive a vocabulary from phonetics; you cannot derive grammar from a vocabulary; a correct use of grammar does not account for good style; and a good style does not supply the content of a piece of prose.

Living beings comprise a whole sequence of levels forming such a hierarchy. Processes at the lowest level are caused by the forces of inanimate nature, and the higher levels control, throughout, the boundary conditions left open by the laws of inanimate nature. The lowest functions of life are those called vegetative. These vegetative functions, sustaining life at its lowest level, leave open—both in plants and in animals—the higher functions of growth and in animals also leave open the operations of muscular actions. Next, in turn, the principles governing muscular actions in animals leave open the integration of such actions to innate patterns of behavior; and, again, such patterns are open in their turn to be shaped by intelligence, while intelligence itself can be made to serve in man the still higher principles of a responsible choice.

Each level relies for its operations on all the levels below it. Each reduces the scope of the one immediately below it by imposing on it a boundary that harnesses it to the service of the next-higher level, and this control is transmitted stage by stage, down to the basic inanimate level.

The principles additional to the domain of inanimate nature are the product of an evolution the most primitive stages of which show only vegetative functions. This evolutionary progression is usually described as an increasing complexity and increasing capacity for keeping the state of the body independent of its surroundings. But if we accept, as I do, the view that living beings form a hierarchy in which each higher level represents a distinctive principle that harnesses the level below it (while being itself irreducible to its lower principles), then the evolutionary sequence gains a new and deeper significance. We can recognize then a strictly defined progression, rising from the inanimate level to ever higher additional principles of life.

This is not to say that the higher levels of life are altogether absent in earlier stages of evolution. They may be present in traces long before they become prominent. Evolution may be seen, then, as a progressive intensification of the higher principles of life. This is what we witness in the development of the embryo and of the growing child—processes akin to evolution.

But this hierarchy of principles raises once more a serious difficulty. It seems impossible to imagine that the sequence of higher principles, transcending further at each stage the laws of inanimate nature, is incipiently present in DNA and ready to be transmitted by it to the offspring. The conception of a blueprint fails to account for the transmission of faculties, like consciousness, which no mechanical device can possess. It is as if the faculty of vision were to be made intelligible to a person born blind by a chapter of sense physiology. It appears, then, that DNA *evokes* the ontogenesis of higher levels, rather than *determining* these levels. And it would follow that the emergence of the kind of hierarchy I have defined here can be only evoked, and not determined, by atomic or molecular accidents. However, this question cannot be argued here.

Understanding a Hierarchy Needs "from-at" Conceptions

I said above that the transcendence of atomism by mechanism is reflected in the fact that the presence of a mechanism is not revealed by its physical-chemical topography. We can say the same thing of all higher levels: their description in terms of any lower level does not tell us of their presence. We can generally descend to the components of a lower level by analyzing a higher level, but the opposite process involves an integration of the principles of the lower level, and this integration may be beyond our powers.

In practice this difficulty may be avoided. To take a common example, suppose that we have repeated a particular word, closely attending to the sound we are making, until these sounds have lost their meaning for us; we can recover this meaning promptly by evoking the context in which the word is commonly used. Consecutive acts of analyzing and integrating are in fact generally used for deepening our understanding of complex entities comprising two or more levels.

Yet the strictly logical difference between two consecutive levels remains. You can look at a text in a language you do not understand and see the letters that form it without being aware of their meaning, but you cannot read a text without seeing the letters that convey its meaning. This shows us two different and mutually exclusive ways of being aware of the text. When we look at words without understanding them we are focusing our attention on them, whereas, when we read the words, our attention is directed to their meaning as part of a language. We are aware then of the words only subsidiarily, as we attend to their meaning. So in the first case we are looking at the words, while in the second we are looking *from* them *at their meaning*: the reader of a text has a *from-at* knowledge of the words' meaning, while he has only a *from* awareness of the words he is reading. Should he be able to shift his attention fully toward the words, these would lose their linguistic meaning for him.

Thus a boundary condition which harnesses the principles of a lower level in the service of a new, higher level establishes a semantic relation between the two levels. The higher comprehends the workings of the lower and thus forms the meaning of the lower. And as we ascend a hierarchy of boundaries, we reach to ever higher levels of meaning. Our understanding of the whole hierarchic edifice keeps deepening as we move upward from stage to stage.

The Sequence of Boundaries Bears on Our Scientific Outlook

The recognition of a whole sequence of irreducible principles transforms the logical steps for understanding the universe of living beings. The idea, which comes to us from Galileo and Gassendi, that all manner of things must ultimately be understood in terms of matter in motion is refuted. The spectacle of physical matter forming the basic tangible ground of the universe is found to be almost empty of meaning. The universal topography of atomic particles (with their velocities and forces) which, according to Laplace, offers us a universal knowledge of all things is seen to contain hardly any knowledge that is of interest. The claims made, following the discovery of DNA, to the effect that all study of life could be reduced eventually to molecular biology, have shown once more that the Laplacean idea of universal knowledge is still the theoretical ideal of the natural sciences; current opposition to these declarations has often seemed to confirm this ideal, by defending the study of the whole organism as being only a temporary approach. But now the analysis of the hierarchy of living things shows that to reduce this hierarchy to ultimate particulars is to wipe out our very sight of it. Such analysis proves this ideal to be both false and destructive.

Each separate level of existence is of course interesting in itself and can be studied in itself. Phenomenology has taught this, by showing how to save higher, less tangible levels of experience by not trying to interpret them in terms of the more tangible things in which their existence is rooted. This method was intended to prevent the reduction of man's mental existence to mechanical structures. The results of the method were abundant and are still flowing, but phenomenology left the ideal of exact science untouched and thus failed to secure the exclusion of its claims. Thus, phenomenological studies remained suspended over an abyss of reductionism. Moreover, the relation of the higher principles to the workings of the lowest levels in which they are rooted was lost from sight altogether.

I have mentioned how a hierarchy controlled by a series of boundary principles should be studied. When examining any higher level, we must remain subsidiarily aware of its grounds in lower levels and, turning our attention to the latter, we must continue to see them as bearing on the levels above them. Such alternation of detailing and integrating admittedly leaves open many dangers. Detailing may lead to pedantic excesses, while too-broad integrations may present us with a meandering impressionism. But the principle of stratified relations does offer at least a rational framework for an inquiry into living things and the products of human thought.

I have said that the analytic descent from higher levels to their subsidiaries is usually feasible to some degree, while the integration of items of a lower level so as to predict their possible meaning in a higher context may be beyond the range of our integrative powers. I may add now that the same things may be seen to have a joint meaning when viewed from one point, but to lack this connection when seen from another point. From an airplane we can see the traces of prehistoric sites which, over the centuries, have been unnoticed by people walking over them; indeed, once he has landed, the pilot himself may no longer see these traces.

The relation of mind to body has a similar structure. The mind-body problem arises from the disparity between the experience of a person observing an external object—for example, a cat—and a neurophysiologist observing the bodily mechanism by means of which the person sees the cat. The difference arises from the fact that the person observing the cat has a *from*-knowledge of the bodily responses evoked by the light in his sensory organs, and this *from*-knowledge integrates the joint meaning of these responses to form the sight of the cat, whereas the neurophysiologist, looking at these responses from outside, has only an *at*-knowledge of them, which, as such, is not integrated to form the sight of the cat. This is the same duality that exists between the airman and the pedestrian in interpreting the same traces, and the same that exists between a person who, when reading a written sentence, sees its meaning and another person who, being ignorant of the language, sees only the writing.

Awareness of mind and body confront us, therefore, with two different things. The mind harnesses neurophysiological mechanisms and is not determined by them. Owing to the existence of two kinds of awareness—the focal and the subsidiary—we can now distinguish sharply between the mind as a "from-at" experience and the subsidiaries of this experience, seen focally as a bodily mechanism. We can see then that, though rooted in the body, the mind is free in its actions—exactly as our common sense knows it to be free.

The mind itself includes an ascending sequence of principles. Its appetitive and intellectual workings are transcended by principles of responsibility. Thus the growth of man to his highest levels is seen to take place along a sequence of rising principles. And we see this evolutionary hierarchy built as a sequence of boundaries, each opening the way to higher achievements by harnessing the strata below them, to which they themselves are not reducible. These boundaries control a rising series of relations which we can understand only by being aware of their constituent parts subsidiarily, as bearing on the upper level which they serve.

The recognition of certain basic impossibilities has laid the foundations of some major principles of physics and chemistry; similarly, recognition of the impossibility of understanding living things in terms of physics and chemistry, far from setting limits to our understanding of life, will guide it in the right direction. And even if the demonstration of this impossibility should prove of no great advantage in the pursuit of discovery, such a demonstration would help to draw a truer image of life and man than that given us by the present basic concepts of biology.

Summary

Mechanisms, whether man-made or morphological, are boundary conditions harnessing the laws of inanimate nature, being themselves irreducible to those laws. The pattern of organic bases in DNA which functions as a genetic code is a boundary condition irreducible to physics and chemistry. Further controlling principles of life may be represented as a hierarchy of boundary conditions extending, in the case of man, to consciousness and responsibility.

References and Notes

1. More precisely, each item consists of one out of four alternatives consisting in two positions of two different compound organic bases.
2. The blueprint carried by the DNA molecule of a particular zygote also prescribes individual features of this organism, which contribute to the sources of selective evolution, but I shall set these features aside here.
3. See P. Weiss, *Proc. Nat. Acad. Sci. U.S.* **42**, 819 (1956).
4. The "field" concept was first used by Spemann (1921) in describing the organizer; Paul Weiss (1923) introduced it for the study of regeneration and extended it (1926) to include ontogeny. See P. Weiss, *Principles of Development* (Holt, New York, 1939), p. 290.
5. See, for example, C. H. Waddington, *The Strategy of the Genes* (Allen & Unwin, London, 1957), particularly the graphic explanation of "genetic assimilation" on page 167.
6. See, for example, M. Polanyi, *Amer. Psychologist* **23** (Jan. 1968) or ———, *The Tacit Dimension* (Doubleday, New York, 1967).