AN EXPLICATION OF THE PHYSIOLOGICAL CONCEPT OF FUNCTION

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ABSTRACT

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By

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The concept of function, although central to physiology, is both vague and ambiguous. The three principal meanings of 'function' are: function$_1$--self-regulated process, function$_2$--the mathematical or logical concept of function, and function$_3$--the teleological concept of function. This dissertation provides a precise quantitative concept of the physiological concept of function$_1$. The method of explication is used to accomplish this. This consists in the clarification or analysis of the pre-systematic term 'function' which produces an explicandum concept. This explicandum is informally defined as a process having an input, output, and transition function, and in which the output is relatively steady, through a mechanism of active compensation. Then the explicandum concept is reconstructed using a theory of variety, whose mathematical structure is similar to that known as information theory. The efficiency of a physiological system is defined as the amount of throughput variety from disturbance to controller to pool, divided by the throughput variety from disturbance to pool without a controller. The amount of self-regulation or function$_1$ is then defined as the efficiency times the throughput variety from disturbance to controller. Examples are given of physiological systems which fit the explicatum; and doubtful cases of $function_1$ are decided as either self-regulating or not on the basis of the explicatum. The place of $function_1$ in the development of the science of physiology is also discussed.

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CHAPTER ONE

THE METHOD OF EXPLICATION

Explication is a method of precise philosophical analysis. Put most briefly, it consists in <u>the replacing of a vague term with a term that is less vague</u>, i.e., <u>more exact</u>. In the philosophy of science it is most commonly used to clarify concepts that occur in such philosophical problems as the analytic-synthetic distinction, or the problem of induction.

The process of explication has three terms in it. These are the pre-systematic term, the explicandum, and the explicatum. The pre-systematic term is the starting point; it consists of some term which is vague and/or ambiguous. From the various meanings or shades of meaning attributed to the pre-systematic term, and for various pragmatic reasons, a particular meaning is separated out and called the 'explicandum.' Based on the meaning of the explicandum, a formalized concept, called the 'explicatum,' is constructed. The exact relationship between the pre-systematic term and the explicandum, and between the explicandum and the explicatum, will be discussed later. Moving from the first through the second to the third of these terms will result in an explication that is much less vague, i.e., more exact, than the pre-systematic term.

Illustrations of explication are well known in contemporary philosophy. The explication of 'analytic statement' by Rudolf Carnap furnishes an example.[1] The notion of an analytic statement is variously defined. Some definitions are: a statement whose opposite is inconceivable, a statement that is necessarily true, a statement true solely in virtue of the meaning of its terms, and, a statement true in all possible worlds. Some philosophers question the defensibility of separating statements into analytic and non-analytic (synthetic). They question the analytic category and offer as evidence for their doubt the existence of statements such as 'Whatever is red is extended' and claim that one cannot decide whether this is an analytic statement or not. Thus the term 'analytic statement' is somewhat problematic and in need of explication. Carnap gave one explication of it in Meaning and Necessity.[2] As the pre-systematic term he took 'analytic statement' with all its variety of definitions. From these he separated out an explicandum called 'L-true' meeting the condition that a sentence is L-true in a semantical system S if and only if that sentence is true in such a way that "its truth can be established on the basis of the semantical rules of the S alone."[3] Then, basing himself on this

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[1]Do not take the use of this example, or other examples of Carnap, as an endorsement of his view on the nature of explication. Although Carnap has contributed much to the method of explication, I do not follow his viewpoint completely regarding the nature of explication. His notion of explication is much broader than the one used in this dissertation.

[2]Rudolf Carnap, Meaning and Necessity (Chicago: University of Chicago Press, 1956), p. 7ff.

[3]Ibid., p. 10.

condition for the explicandum, he constructed a formalized concept of L-true in terms of first-order predicate logic. An L-true sentence in a system is defined in terms of that sentence holding in every state-description in the system.[4] In this example, then, Carnap replaced the vague term 'analytic' by the more exact term 'L-true' as defined in terms of state-descriptions.

Another explication which will serve as an illustration is the explication of 'probability' by Carnap. In Logical Foundations of Probability,[5] Carnap takes the pre-systematic concept of probability, which is vague and ambiguous, and separates out as an explicandum the logical concept of probability, which he labels 'probability$_1$.' He sets down three conventions which characterize this explicandum. Then a formalized definition of degree of confirmation, c*(h,e), is given in terms of structure-descriptions in predicate logic. This illustration again shows how an explication replaces a vague term by one less vague.

In order to describe an explication more fully, it will be divided into two aspects. The first aspect is the clarificatory one, the move from the pre-systematic term to the explicandum term. The second is the constructive one, moving from the explicandum to the explicatum. The first aspect, the selection of an explicandum, has several characteristics which will be discussed in detail. The second aspect, the selection of an explicatum, also has characteristics

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[4] Ibid.

[5] Rudolf Carnap, Logical Foundations of Probability (Chicago: University of Chicago Press, 1962).

which will be more fully discussed. Both aspects are essential for any explication.[6]

Both aspects of an explication are centered around terms. Terms, however, must be viewed as terms-cum-rules. A grouping of consonants and vowels spelling 'probability' has no meaning unless associated with some rules of usage, both syntactical and semantic. Thus when we speak of a term being ambiguous we are referring to the term with its rules of usage; and we are saying that there is more than one set of rules of usage associated with the term, i.e., the term is ambiguous. A term should be viewed as a vehicle to be used according to rules. The expression 'term-rule' would more accurately serve us here to bring out this fact.

Now let us examine in detail the clarificatory aspect of explication, i.e., the move from a pre-systematic term to the selection of an explicandum.

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[6]There are a few philosophers (Michael Scriven, Gilbert Ryle, and others) who do not feel the constructive aspect is essential to an explication. Scriven, for example, distinguishes between 'content analysis' and 'context analysis.' The content analysis or formal analyst puts up a neat and simple model in symbolic logic of the statements under consideration. Complementary to this is context analysis. "Context analysis is undertaken in the belief that the meaning of terms or concepts or logical problems can only be thoroughly understood if we include a meticulous examination of the circumstances in which they occur" (Michael Scriven, "Definitions, Explanations, and Theories" in Minnesota Studies in Philosophy of Science, Vol. II, ed. by H. Feigl, M. Scriven, and G. Maxwell (Minneapolis: University of Minnesota Press, 1958), p. 100). Problems of meaning analysis "can be solved only by reference to detailed and varied examples described with considerable care" (*ibid*., p. 101). In my opinion, much of the antipathy these philosophers show toward the reconstructive aspect is due to a failure on their part to realize and a failure on the part of those philosophers who do use reconstructions to emphasize, the importance of the clarification apsect.

The clarification eliminates ambiguity. A term is ambiguous when it has two or more distinct meanings, i.e., semantic rules of usage, associated with it. Thus 'pen' may mean a writing instrument or an enclosure for animals. The set of distinct meanings constitutes the 'range of ambiguity' of the term. Thus 'analytic statement' has a range of ambiguity consisting of all the distinct meanings associated with the expression 'analytic statement.' Ideally, each meaning would be associated with only one expression. To achieve this effect, some authors use subscripts to distinguish term-rules. Thus Carnap saw that the pre-systematic term 'probability' had a range of ambiguity consisting of two distinct meanings and the first meaning, logical probability, he associated with the expression 'probability$_1$,' and the second meaning, empirical probability, he associated with the expression 'probability$_2$.'

The pre-systematic term may also be vague, i.e., one cannot be sure whether a given object is included in or is not included in the extension of the term. Here it is not a question of two or more rules applying, as with ambiguity, but rather it is a question of whether a particular rule applies or not. 'Tall' is a vague term since one cannot say whether a person whose height is 5 feet, 11 inches is tall or not.

In the clarificatory aspect, the range of ambiguity is established, and <u>one</u> of the meanings is selected. This eliminates the ambiguity of the pre-systematic term. Then an informal definition is formulated. This is a statement of the rules of usage for the term selected and this serves to eliminate some of the vagueness in that particular meaning. This resulting term-rule is the explicandum.

In the clarification stage of explication, informal discourse is used throughout. The pre-systematic term is in ordinary language and the explicandum with its informal definition is phrased in informal discourse. This is in contrast to the second stage, the constructive one, where formal discourse comes into use, and the explicatum, the goal of this stage, is put into some sort of canonical notation.

The explicandum then is a term which has associated with it some list of characteristics or conditions which will act as a guide to the formalized reconstruction which follows. This is the goal of the clarificatory stage. What is the basis for deciding which meaning from the range of ambiguity will be selected? And what form will the preliminary definition take?

The selection of one particular meaning from the range of ambiguity is based upon pragmatic considerations, especially the intent of the explicator and the systematic context, i.e., the discipline or specialty which the explicator selects. The person explicating may have various reasons for selecting some particular meaning as explicandum such as practical relevance to some contemporary problem or a feeling that this is the most important or often-used meaning. The systematic context, on the other hand, provides a more objective basis for deciding on an explicandum. Thus if the field of inductive logic is chosen as the systematic context, then one can advance various reasons which make the use of probability$_1$ consistent with the aims of inductive logic. Once one has narrowed down the area of study to a special field, then an examination of the literature of that field

will guide one in formulating an informal definition of the explicandum. Given a systematic context, the clarification will rest upon a description of facts concerning the actual usage of the term. A thorough investigation must be conducted to accurately determine the meaning used in the field; one must perform a careful examination of as much source material as possible. Unfortunately, many philosophers do not emphasize this clarificatory aspect of explication, with the result that the final explicatum lacks relevance. "Too few case studies and other factual inquiries are undertaken, to serve as a check of correctness and as a stimulus to more profound and refined accounts concerning concept-formation in science."[7]

The explicandum may and will deviate somewhat from the presystematic term. The systematic context may tell us which of the particular meanings in the range of ambiguity is actually used, but within that particular meaning some or a lot of vagueness will exist (else why explicate?) and thus no strict guidelines as to the informal definition are present. The explicator may try to formulate a definition which will prove fruitful in its consequences, and simple in its form, while remaining as faithful as is possible to accepted usage in the field.

The explicandum, though a clarified version of the presystematic term, still possesses some vagueness. There are some objects of which we cannot say, on the basis of the explicandum's definition,

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[7]P. H. Nidditch, ed., The Philosophy of Science (London: Oxford University Press, 1968), p. 7.

whether they are or are not cases of the explicandum. This deficiency is due mainly to the fact that the explicandum's definition is framed in informal discourse.

Having examined in detail the clarificatory aspect of explication, let us now examine the constructive aspect, i.e., the move from the explicandum to the selection of an explicatum.

The second aspect of explication, the constructive aspect, begins with the explicandum and its informal definition. The explicandum is extensionally vague. Either there are some objects which could be said to be both an instance and not an instance of the explicandum, or there are some objects which seem not to be instances nor non-instances of the explicandum. By explicandum we mean the explicandum-cum-rules, i.e., the explicandum and its associated informal definition. More precisely, it is this informal definition which is vague. And it is vague because of the informal discourse in which it is framed. Thus if we replace the informal definition of the explicandum by a formalized definition we can eliminate this vagueness to a great extent. This is the goal of the constructive stage of explication.

The explicatum, compared to the explicandum, is clear and precise. Every individual is clearly either a member or not. This is achieved by the formalized definition of the explicatum. This process involves choosing a formalism which will be used in the explicatum, e.g., mathematics, predicate logic, probability theory, etc. The explicatum will then be introduced into this rigorously connected system of concepts with rigorous semantic rules.

Which type of concept will provide the most precise explicatum? If we consider 'precise' to mean "being exactly that and neither more nor less," or "being just that and no other"[8] (italics mine), we can see that the more things we can separate something from the more precise is our knowledge of that thing. By 'separate' we mean also 'relate' in the sense of 'differentiate.' Now given any single concept, e.g., warm, we can say that something is or is not warm. Thus some warm object can be differentiated from only one class, the non-warm. Now with a comparative concept we can say that an object x is warmer than an object y. And given the transitivity of this ordinal ranking, we could differentiate x from all the objects below y in warmth ranking. With a quantitative concept of temperature, however, we can differentiate a particular object from many others, i.e., by stating that an object is 20°C we know it is not 21°, or 2,000°, or 25.5°, or 26.6984°, etc. Thus the constructed explicatum concept can be of three types, classificatory, comparative, or quantitative. The classificatory concept classifies into two or several mutually exclusive kinds. Comparative concepts propose a comparison of two objects in the form of a statement that asserts a rank ordering of the two objects without the use of numerical values. A quantitative concept describes an object with the help of numerical values. Now ideally the quantitative concept is the most precise and thus most desirable. And assuming that the explicandum can be formalized with such a concept, it would be the most desirable,

[8]Jess Stein, ed., The Random House Dictionary of the English Language (New York: Random House, 1966), p. 1131.

although any of the three types which have precise rules of usage could be used.

The explicatum is constructed with an eye on the informal definition of the explicandum. But just what is the relationship between the explicatum and the explicandum? The relationship is best expressed in terms of a correspondence condition such as the one given by Joseph Hanna. Hanna characterized this correspondence condition as "requiring that the extension of the explicatum correspond (via an effective translation) to the extension of the explicandum (to the extent that the latter is clear and consistent)."[9] In other words, there is an extensional correspondence of explicandum to explicatum in all cases where the object is clearly in or not in the explicandum class, and in those cases where it is not clear if some object is in the explicandum class, then membership in the explicatum class decides whether that object is in the explicandum class or not.

In summary then, an explication has two stages, the first involving sorting out the various meanings of the pre-systematic term, selecting one of these meanings, and giving it an informal definition. This is the selection of the explicandum. The second stage involves the construction of a formalized definition which will correspond to the explicandum to the extent that the explicandum is complete and consistent.

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[9]Joseph Hanna, "An Explication of 'Explication,'" <u>Philosophy of Science</u>, 35 (1968), p. 43.

This above pattern of explication will be followed throughout this dissertation. We have represented this below.

clarification

Range of ambiguity of 'function'
$$\left\{\begin{array}{ll} \text{function}_1\text{:} & \text{self-regulated process} \\ \text{function}_2\text{:} & \text{mathematical} \\ \text{function}_3\text{:} & \text{necessary condition} \end{array}\right.$$

+ systematic context of contemporary physiology (Claude Bernard) $\Longrightarrow$ function_1

construction

$$\text{function}_1 \xrightarrow[\text{theory}]{\text{variety}} S(D;C;P)$$

First, the pre-systematic term 'function,' which is both vague and ambiguous, is analyzed into three principal meanings. In the context of the science of physiology, we select function_1 and then give an informal definition of it. Secondly, a formalized definition of amount of self-regulation, S, is constructed in terms of the theory of variety.

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The goal of an explication is to produce an explicatum. How well this goal is achieved can be evaluated in terms of the adequacy of the explicatum. Three criteria of adequacy for any explicatum are: relevance, preciseness, and simplicity. Carl Hempel discusses the first two of these when he characterizes explication as

> a linguistic proposal which itself is neither true nor false, but for which adequacy is claimed in two respects: First in the sense that the explication provides a reasonably close analysis of the commonly accepted meaning of the explicandum--and this claim implies an empirical assertion; and secondly in the sense that the explication achieves a "rational reconstruction" of the explicandum, i.e., that it provides, together perhaps with other explications, a general conceptual framework which permits a consistent and precise restatement and theoretical systematization of the contexts in which the explicandum is used--and this claim implies at least an assertion of a logical character.[10]

The first criterion mentioned by Hempel, relevance, is more complex than his description implies. First, the explicatum should correspond to the explicandum and secondly, the explicandum should reflect actual usage. But actual usage is vague and ambiguous; this is why one explicates. Thus pragmatic decisions are made, especially regarding which area of study is to be selected. This was earlier called the 'systematic context.' Given this selection, then it becomes an "empirical assertion" whether the explicandum does in fact provide an analysis of that term in that context. The point that needs to be stressed is that the explicatum cannot be relevant to rejected meanings of the pre-systematic term. To claim that Tarski's explicatum for

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[10]Carl Hempel, "Problems and Changes in the Empiricist Criterion of Meaning," Revue Internationale de Philosophie, 11 (1950), 61.

'truth' is not relevant to all the everyday meanings of that term is to neglect to consider the process of clarification which must occur in an explication. On the other hand, to formulate an explicandum which does not reflect actual usage in some designated area, or to construct an explicatum which does not correspond to the explicandum is to fail to meet the criterion of relevance. Relevance then includes correspondence of explicatum to explicandum and an accurate reflection of actual usage in some context.

The explicatum must be less vague than the explicandum. This means that cases where it is not decidable whether an object belongs to the explicandum class must be decidable in terms of the explicatum class. Also, the explicatum should be defined in terms of some formalized language. Finally, the explicatum should use as precise a type of concept as possible.

The explications of 'function' which have appeared in the last decade or two are woefully inadequate on the basis of these first two criteria. First, they lack relevance. These explications of 'function' are based on a small number of stereotyped statements, such as 'The function of the heart is to pump blood.' The historical and linguistic richness of the language of physiology, a thorough analysis of the entire corpus of physiological literature, is ignored. In a word, the clarification is not well done. Secondly, the explications do not provide a more precise substitute. Most are translations from ordinary language to ordinary language. The logical formalism often involves nothing more than the notion of a necessary condition. Thus the constructive phase is also inadequate.

In this dissertation we will try to redress the superficial treatment found in explications of 'function.' Since the science of physiology is universally defined as the study of functions in living organisms, it stands to reason that the concept of function merits more than superficial treatment.

The third criterion of adequacy is simplicity. The simplicity of an explicatum refers to both the simplicity of the form of its definition and the simplicity of the form of the laws which connect it with other concepts. Simplicity is usually a secondary consideration however. When the other two criteria are equally satisfied by a pair of explicata then we would choose between the pair on the basis of simplicity. What the simplicity criterion does rule out is unnecessary complicated explicata.

In order to achieve an adequate explication of 'function,' we will be dealing in the literature of the science of physiology and discussing its models, theories, and empirical basis. To some readers this dissertation may thus appear to be a treatise in physiology. Our aim, however, is always to be performing an explication, a metascientific inquiry. But an adequate job of explication, as we have mentioned above, requires a thorough study of the language actually used by physiologists. Even though it is metascience, an explication must rely upon scientific work to emphasize the systematic context and to do a thorough job of clarificatory meaning analysis.

CHAPTER TWO

CLARIFICATION OF 'FUNCTION'

Introduction

If one surveys the literature in the philosophy of science, one can find under the heading of "the philosophical problem of function in biology" a variety of problems being discussed. First of all, the subject matter varies. Some authors discuss functional explanations, others discuss functional statements, while others discuss the concept of function itself. Secondly, the questions investigated in the subject matter vary. Some investigate whether functional locutions (i.e., explanations, statements, or concepts) in biology are different from the locutions of other branches of science. Some investigate whether functional locutions are empirically verifiable. Others ask whether functional locutions can be replaced by non-biological locutions. Still others seek to analyze or explicate the meaning of functional locutions. Thirdly, for each one of these questions, one can usually find more than one solution given. One can see that any discussion of 'function' such as this dissertation purports to provide must clearly state what subject matter and problem is being treated. The purpose of this introduction is to indicate that what we intend to discuss is the concept of function as it occurs in one of the branches of the biological sciences, viz.,

physiology. The problem we have set for ourselves is that of explicating that concept, i.e., giving a precise expression of its meaning.

The various attempts to explicate or analyze functional statements and functional explanations have also, directly or indirectly, involved some treatment of the concept of function itself. This present dissertation however deals directly with the concept of function. This is not to deny that it could provide a basis for a treatment of functional statements or functional explanations. However, when functional statements and functional explanations are used as examples in this dissertation, they are only examples to illustrate usages of the concept of function itself.

Throughout this chapter we are going to deal with the clarificatory aspect of our explication. The pre-systematic meanings of the term 'function' will be discussed. Then, using the science of physiology as our systematic context, we will analyze the meanings of 'function' to determine which meaning is used by physiologists and then this meaning will be expressed as an informal definition. This definition will constitute our explicandum and the first phase of the explication will be completed. The second phase, the construction of a formal explicatum, will occur in Chapter Four.

All attempts to explicate or analyze functional locutions have assumed that there is only one "correct" meaning for the term 'function.' This assumption has led to much useless debate in discussions over the problem of function in biology. It is not unusual for a term to have

two or more distinctly different meanings; a search for the "one correct meaning" may never be completed if the term has more than one correct meaning at the outset.

> It has repeatedly occurred in the history of science that a vehement but futile controversy arose between the proponents of two or more explicata who shared the erroneous belief that they had the same explicandum; when finally it became clear that they meant different explicanda, unfortunately designated by the same term, and that the different explicata were hence compatible and moreover were found to be equally fruitful scientific concepts, the controversy evaporated into nothing.[1]

The working scientist, in using the same term, e.g., 'function,' may not always assume the same meaning for it each time he uses it. He may alternate between various meanings, depending on the context. What this chapter is trying to capture is that meaning of 'function' which the physiologist assumes in the context of technical physiology. This is what we mean by the "physiological" concept of function. We want to describe the meaning assumed by the physiologist in the context of the theroetical framework of scientific physiology.

The debate among earlier physicists concerning whether 'mv' or 'mv^2' was the correct formal expression or explicatum for 'quantity of motion' ('vis viva') is a typical example of the futile controversy that arises when men assume that a term can have only one meaning. In fact the explicata, 'mv' and 'mv^2' were found to correspond to two different explicanda, which we now call 'momentum' and 'kinetic energy' respectively. Carnap also sees the same futile debate occurring in

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[1]Rudolf Carnap, Logical Foundations of Probability (Chicago: University of Chicago Press, 1962), p. 26.

regard to the concept of probability, i.e., debate over whether the relative frequency view or the logical view is the correct explicatum for 'probability.' Carnap emphasizes that both explicata are correct because there are two distinct explicanda; each explicatum applies to a different explicandum however. Now with respect to the term 'function,' the same type of debate has been raging. Some argue for the negative-feedback model, some for mental action or purpose, and some for the concept of necessary condition. Each of the proponents is assuming that there is only one correct meaning for 'function,' in biology. What we would like to show is that there are three possible meanings for 'function' in biology, and more specifically, in physiology.

At the present time the debate over the meaning of 'function' seems to have come to a stalemate between two camps. On the one side are the non-teleologists maintaining a hard-nosed empiricism. On their view, 'function' means activity. The 'function of x' means what x does. Molecular biologists, and experimental physiologists hold this position. On the other hand there are the teleologists, who hold that 'function' means something more than just what x does. Here we find philosophers of science, more traditional philosophers, and some general biologists. The surplus meaning of 'function' has been claimed to be: (1) the idea of purpose; (2) the role played in the whole; (3) necessary condition; or (4) usual condition. Here is an example from the first camp:

> In planning the book presented here, the editors have tried to find some unifying approach which would give a common interest to these diverse ways of studying the blood. The idea which seemed to provide most promise was the idea of function. Though one hesitates to ask

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> such a teleological question as "What is the blood _for_?" it is perfectly legitimate to ask "What does the blood _do_?" . . . If the idea of function were the predominant one, then structural differences become less important, since the same vital function can be adequately performed by chemically different substances.[2]

According to this view, the legitimate physiological concept of function is expressed by "What does x do?" Carl Hempel, and many other philosophers, reject this meaning of 'function.' According to these writers, accepting the above account of the meaning of 'function' as "What x does" would force us to accept as true the statement that "The heartbeat has the function of producing heart sounds; for the heartbeat has that effect."[3] Hempel's claim is that no physiologist would accept that last statement, and thus the physiologist must have in mind a concept of function different from "What x does."

Thus we have the solutions to the problem of the meaning of 'function' in physiology split into two camps. On the one hand there are those holding that the 'function of x' means what x does. On the other hand are those holding that the 'function of x' means what x does plus some surplus meaning. This latter camp is then divided by the different explications of this surplus meaning.

We believe that the above dichotomy of the solutions to the problem of 'function' results from an inaccurate analysis of function locutions by both sides of the discussion. This over-simplified dichotomy shows that physiologists, while experts at using the concept

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[2]R. G. MacFarlane and A. H. T. Robb-Smith, eds., _Functions of the Blood_ (New York: Academic Press, 1961), p. vii.

[3]Carl Hempel, _Aspects of Scientific Explanation_ (New York: Free Press, 1965), p. 305.

of function, are quite naive in their analysis of it. It also shows that the philosophers of science are naive in assuming that 'function' has only one meaning, i.e., the teleological one. For the physiologist to give as the meaning of 'function' the very vague definition, "What x does," and expect this to be the meaning of the most fundamental term in a very exact science, i.e., physiology, is very naive. The science of physiology requires a more precise concept of function, else how distinguish physiology from embryology, or animal behavior, which also study "What x does." In other words, the concept of function as "What x does" is not adequate as a foundational concept for the science of physiology. Also, the meanings of 'function' proposed by the philosophers of science also include the notion of "What x does." The 'function of x' according to these men means something like 'What x does that has a purpose' or 'What x does that is a necessary condition for survival.' Thus to say that the first camp holds that 'function' means activity while the second camp holds that 'function' does not mean activity is incorrect and misleading. The physiologists, who claim that the 'function of x' means "What x does" are neglecting to fully state their meaning of 'function.' It is what x does as x, i.e., the activity proper to x that is the function. How one decides the activities that are proper to x is of course an empirical question, but these activities must be such that over a length of time x is still recognizable as x, i.e., x maintains itself. Thus, upon closer analysis, we see that all the schools of thought debating the question of the meaning of 'function' are similar in that the 'function of x' means

"What x does" plus some surplus meaning. The real debate arises when it comes to explicating this surplus meaning.

A Survey of the Usages of 'Function'

This section provides a survey of the various meanings of the term 'function.' By a judicious selection of illustrations, the three principal meanings of 'function' in ordinary language will be established. Then, by an examination of the scientific language of physiology, the principal meaning of 'function' in physiology will be established. Two other less common physiological meanings will also be shown. In this way the range of ambiguity of the term 'function' will be clearly set forth.

It is important to note the influence that everyday language has had on technical scientific language. From a linguistic viewpoint, scientific language represents a correction of some of the "objectionable" features of everyday language such as vagueness and ambiguity.

> All men come to the scientific enterprise with a highly elaborated system for ordering events and perceptions. As adult human beings they have acquired an ingrained way of looking at the world--a cultural patterning of the environment which all of us use as the basic framework for making statements about the world of objects and events. This archaic view of the world, a protopsychology and protophilosophy, is the initial source of statements and generalizations in science. It does not magically disappear in the laboratory or in the library. The scientist does not approach his scientific universe in a linguistic vacuum, and for this reason the usefulness of the vernacular vocabulary for scientific activity must be examined.[4]

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[4]George Mandler and William Kessen, _The Language of Psychology_ (New York: John Wiley & Sons, 1959), p. 9.

Thus we can conclude that the everyday meanings of 'function' should have some relationship to the scientific meanings. One of the purposes of this section is to show this relationship. In particular it will be seen that just as there are three principal meanings of 'function' in ordinary language, so these three meanings have their correlates in the scientific language, and that the primary meaning in ordinary language corresponds to the primary meaning in physiology. Also, a teleological interpretation of 'function' is found in both the ordinary and scientific language.

Pre-Scientific Usages

The earliest usages of the English word 'function' reveal that the meaning was restricted to persons who had some administrative position to fulfill. The following excerpt, dated 1533, exemplifies this: "because the sayntes be al departed hence . . . and be no lenger of our funccion."[5] The context states that a certain man wanted to pray to living persons rather than dead saints because these living persons have the same 'funccion,' i.e., activity, as we do, whereas the saints, as dead, do not have this activity. In 1574 we find, "The contraveners hereof, if they be ministers, to be secludit fra the function."[6] Thus in its original meaning, 'function' meant "The kind of action proper to a person as belonging to a particular class, esp. to the holder of any office; hence, the office itself."[7]

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[5] Oxford English Dictionary, Vol. IV (Oxford: Oxford University Press, 1933), p. 602.

[6] Ibid.

[7] Ibid.

A modern dictionary definition of the noun 'function' is given as "the kind of action or activity proper to a person, thing, or institution."[8] Thus we say, 'The chief function of a king is to rule his people' or 'The function of that wooden object is to steer the ship.' In both sentences one is referring to the activity and the object or entity exhibiting that activity or capable of exhibiting that activity. A function in this sense is thus first of all an action or activity of a certain kind. Secondly, this activity is "proper" to some entity, i.e., some particular type of entity. It is expected of some entity, e, that it exhibit activity a_e. Or perhaps all occurrences of e were followed by a_e; or again, e may have been designed to perform activity a_e. The entity e can be of any sort--human, animal, plant, or institution; in a word, any recognizable structure. What we have in this sense then is some entity or structure, e, which exhibits an activity, a_e, proper to its kind. The verb 'function' correspondingly means "to perform a specified action or activity."[9]

A second sense of the noun 'function' is given as "a factor related to or dependent upon other factors."[10] Here one is not talking about an activity but a relationship between "factors." Thus we say, 'Price is a function of supply and demand.' Since "related to or dependent upon" is such a vague expression, the detailed applications of this meaning of 'function,' i.e., its detailed meanings, are manifold.

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[8]Jess Stein, ed., The Random House Dictionary of the English Language (New York: Random House, 1966), p. 574.

[9]*Ibid*.

[10]*Ibid*.

If the relation is that of causation, for example, then 'Suicide rate is a function of the amount of social cohesion in a society' means 'Suicide rate is an effect of the amount of social cohesion in a society.' This is equivalent, of course, to 'A change in the amount of social cohesion in a society causes a change in the suicide rate.' If the relation is one of correlation rather than causation there is a corresponding change in the detailed meaning of this sense of 'function.'

There is a third group of meanings given to 'function.' Another dictionary, gives us a definition of 'function' as "special purpose."[11] Another related meaning of 'function' is given as "One of a group of related actions contributing to a larger action."[12] Now there is a somewhat subtle difference between these last two definitions. The former defines a function as a purpose while the latter defines a function as an activity which has a purpose. This latter definition thereby combines both the meaning of our first definition of 'function,' i.e., special activity, and this third meaning, i.e., purpose.

Thus, while there is vagueness and ambiguity in ordinary usages of 'function,' three definitions seem to be distinguishable.

1. Function as special activity;
2. Function as a co-variation;
3. Function as a purpose or contribution to the whole.

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[11] The New Merriam-Webster Pocket Dictionary (New York: G. & C. Merriam Co., 1971), p. 204.

[12] P. B. Grove, ed., Webster's Third New International Dictionary (Springfield, Mass.: G. & C. Merriam Co., 1965), p. 921.

Scientific Usages

Now let us examine examples of the meaning of 'function' in physiology. Among these are some examples of 'function' as referring to a self-regulated biochemical process. This we will call 'function$_1$.' This concept of function$_1$ is the most important one, from a semantical and a methodological point of view for the science of physiology. We will then give illustrations of two other concepts which occasionally occur in the literature of physiology. These two concepts will illustrate the meanings we do not wish to attribute to the term 'function.' These two other concepts are called 'function$_2$' and 'function$_3$.' Function$_2$ is the concept of a process that is dependent upon or which varies with some other factor; y is a function of x. Function$_3$ refers to a process which serves some utility or usefulness, i.e., is a necessary condition for the survival of the organism.

The best illustrations of function$_1$ are the so-called vital functions, e.g., circulation, digestion, excretion, reproduction, and respiration. It is with this meaning in mind that biologists and physiologists can say "Life . . . depends on the regular, reliable performance of certain functions."[13] The biologist speaking in this quote is referring to the above-mentioned vital functions. Notice too that in living organisms these functions must be performed in a regular and reliable way. These functions must be regulated or controlled so that in spite of environmental vagaries, the activities will be maintained.

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[13]Garrett Hardin, Biology, Its Principles and Implications (San Francisco: W. H. Freeman, 1966), p. 50.

A modern physiology textbook has the title Animal Function: Principles and Adaptations.[14] In the preface of this textbook the authors state their purpose as that of describing the "functional features of whole organisms."[15] They state that "The organization of this book emphasizes physiological process."[16] One biologist summarized the contemporary field by saying that "major emphasis recently has been centered about the relation of detailed molecular structure to biological function."[17] Often, anatomical parts are considered as the "seats" of the functions. Thus we have expressions like 'kidney function.' "The way the kidney works is described clearly and explicitly in this book--a story of vertebrate evolution and adaptation seen through kidney function."[18] The way the kidney works is described in the next paragraph following the above quote, and concludes by saying that "Through mechanisms of filtration and reabsorption, the balance of the internal environment is maintained."[19]

Now when contemporary physiologists speak of the activities in a living organism they are not referring to the overt behavior as

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[14]Malcolm Gordon et al., Animal Function: Principles and Adaptations (London: MacMillan, 1968).

[15]Ibid., p. v.

[16]Ibid., p. vi.

[17]Talbot H. Waterman, "Coda," in Theoretical and Mathematical Biology, ed. by Talbot H. Waterman and Harold J. Morowitz (New York: Blaisdell Publishing Co., 1965), p. 399.

[18]Evelyn Shaw, "Foreword" in Homer W. Smith, From Fish to Philosopher (Garden City, N.Y.: Doubleday & Co., 1961), p. xi.

[19]Ibid.

studied for example by ethologists. One author states "However, as the skin of an amphibian is permeable to water, water loss becomes a critical problem that restricts amphibian activity and physiology."[20] Here the external behavior of the frog is distinguished from its internal processes. A similar distinction is found in the following excerpt: "Those leptodactylids that have evolved in the frog vacuum of Australia have radiated into such a variety of morphological, behavioral, and physiological types, that as expected, some forms do tolerate colder conditions, though few tolerate severe conditions."[21] The "physiological types" refers to types of internal processes and they are contrasted with morphological and behavioral types. Another author makes a further distinction: "Little is known of the behavior, physiology, or ecology of these forms, except for some observations on reproduction."[22]

Since the activities or processes of physiology are not behavioral, i.e., properties of whole organisms, of what are they properties? We would like to show that they are properties of chemical substances, that physiological processes, i.e., $functions_1$, are biochemical processes. "Physiology . . . must go deeper and deeper into the physical and chemical phenomena which in their integration make up

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[20]B. H. Brattstrom, "Amphibia," in Comparative Physiology of Thermoregulation, Vol. I, ed. by G. C. Whittow (New York: Academic Press, 1970), p. 135.

[21]Ibid., p. 141.

[22]Ibid.

the vital processes."[23] In an article entitled "The Physiology of the Cell Nucleus," the author states, "We have a rough outline of the chemical composition of the nucleus and can attempt realistically to assign physiological activities to known chemical fractions."[24] We can see, then, that the meaning of function_1 refers to biochemical processes and is contrasted with behavioral activities.

The functions of living organisms especially in higher animals are interrelated. Walter Cannon put it this way:

> Investigators of the functions of higher organisms are concerned with extremely complicated processes. Not only are there complex interrelations among the processes participating in the life of these organisms but also the organisms themselves are responsive to external conditions imposed upon them, conditions which may further confuse the total situation.[25]

An earlier quotation was used to refer to the "integration of functions" by means of the nervous and endocrine systems. This provides a flow of communication between the functions or physiological processes.

One last characteristic of physiological processes is their self-regulation. We said earlier that "Life . . . depends on the regular, reliable performance of certain functions."[26] The functions

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[23]E. S. G. Barron, ed., Modern Trends in Physiology and Biochemistry (New York: Academic Press, 1952), p. vii.

[24]Daniel Mazia, "Physiology of the Cell Nucleus," in Barron, op. cit., p. 118.

[25]Walter B. Cannon, The Way of An Investigator (New York: Hafner Publishing Co., 1945), p. 129.

[26]Hardin, op. cit., p. 50.

in living beings must perform with regularity. E. F. Adolph, who has spent most of his life studying physiological regulation, says, "In the body, hundreds of thousands of processes are automatically regulated. . . . In every organ, such as kidneys, hundreds of unit processes are regulated also. . . . In every cell, hundreds of separable processes are regulated."[27] Thus physiology studies these self-regulated processes, and thus the 'functions' studied by physiology, i.e., functions_1, have as one of their characteristics that they follow a pattern of self-regulation. The details of this pattern of self-regulation will be given later. The general pattern used is also termed "goal-directed," e.g., maintenance of a particular amount of blood pressure is a "goal" which the process of circulation achieves, using various mechanisms.

We have tried to bring out as sharply as possible the concept of function_1; it is a self-regulated biochemical process which is interrelated with other similar processes in the living organism. It is on the basis of this concept that 'physiological' is sometimes used analogically, i.e., meaning living, <u>in vivo</u>, or metabolic. Thus we find the statement made that "As far as we can tell, these K_m values may be as much as 100 times higher than probable physiological concentrations, and hence do not even approximate the <u>in vivo</u> condition at low temperature."[28] The 'physiological concentration' is the one found <u>in vivo</u>.

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[27]E. F. Adolph, <u>Origins of Physiological Regulations</u> (New York: Academic Press, 1968), p. 3.

[28]F. E. J. Fry and P. W. Hochachka, "Fish" in Whittow, <u>op. cit</u>., Vol. I, p. 120.

'Physiological' can thus be used analogically for "living." The following quotation implies that physiological death is complete death, i.e., when life is completely stopped. "Most workers have distinguished between an ecological or behavioral death point, where recovery is possible after locomotor failure (onset of spasms, elimination of righting response), and physiological death, beyond which recovery is impossible (lethal temperature)."[29] Thus a "physiological" death is that case where recovery, i.e., regulation, has ceased; the idea of regulation is the key aspect being used in this concept of death. Thus there are analogical usages which cluster around the principal meaning of function$_1$: a regulated biochemical process in living organisms.

Having given some positive examples of function$_1$ we would like now to introduce two other meanings of 'function,' neither of which are the important physiological ones.

Sometimes in the writings of physiologists one finds statements such as "the unidirectional influx of cholesterol is plotted as a function of cholesterol concentration in Figure 2."[30] Or again, "In developing this method we have studied the distribution of CO between blood and muscle as a function of arterial oxygen tensions in the anesthetized

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[29]Brattstrom, op. cit., p. 147.

[30]S. G. Schultz and C. K. Strecher, "Cholesterol and Bile Salt Influxes Across Brush Border of Rabbit Jejunum," American Journal of Physiology, CCXX (1971), 61.

dog."[31] One author speaks of the "autocorrelation function" using 'function' in this mathematical sense.[32]

These illustrations are expressions of the concept of function$_2$ and are based upon its principal meaning found in the mathematical concept of function. In mathematics, the term 'function' is defined as any relation between two classes of elements such that for every member of one of the classes there is a uniquely determined member of the other class. In '$y = x^2$,' 'y' is a function of 'x' since for every value of the "independent" variable, 'x,' there is one and only one value for the "dependent" variable 'y.' In a non-mathematical fashion this same concept of function is used analogously to mean any relation of dependence or interdependence between two or more variable factors, whether or not these factors are measurable.

This concept of function$_2$ is <u>not</u> the one we intend to explicate. It is not a peculiarly physiological concept; this concept of function is used throughout most of the natural science. Its occurrence is easily recognizable and it is not difficult to distinguish it from the other concepts of function. We are not of course claiming that this concept is of little value in the sciences. Neither are we claiming that there are no analogies between function$_2$ and other concepts of function.

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[31] <u>Ibid</u>., p. 66.

[32] Yona Mahler and Schlomo Rogel, "Computer Analysis of Myocardial Tension and Pressure Variations in Atrial Fibrillation," <u>Journal of Applied Physiology</u>, XXIX (1970), 77.

The third principal meaning of 'function,' the teleological concept, is also one that we are not considering as a desired explicandum. This concept of function$_3$ is also the one almost universally dealt with in explications of 'function' by philosophers of science. A pre-occupation with this concept of function by philosophers of science is the chief cause of the current irrelevance of philosophy of biology to the science of biology.

Very rarely in the technical journals of physiology one finds statements such as "The significance of these reactions in sperm is not known. It is possible that they are important in the testes or male ducts, and have no function after ejaculation."[33] This is 'function' meaning significance for the whole or role played in the whole. "In considering the role of the nucleus in the nondividing cell, it was a problem to discover whether it had any function at all."[34] If one reads the less technical literature of physiology and biology, e.g., introductory textbooks, one finds more illustrations of the use of function$_3$. Garrett Hardin, for example, states that "the function of the blood vessels [in the small intestine] will be considered first."[35] Then follows the statement that amino acids and simple sugars pass through the villi and into blood vessels, where they are carried throughout the body.

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[33]R. R. Hathaway and E. M. Chamberlain, Jr., "Bull Seminal Plasma and the Regulation of 17 β-Estradiol Dehydrogenase Activity in Spermatozoa," Biology of Reproduction, II (1970), 164.

[34]Mazia, op. cit., p. 109.

[35]Hardin, op. cit., p. 485.

The concept of purpose is sometimes given as the meaning of 'function.' By 'purpose' we are referring to the conscious goals of human beings, which goals influence the behavior of the human beings that entertain them. Thus when a college student takes a certain curriculum as an undergraduate in order to prepare himself for medical school, we say he has a purpose to what he is doing. His entrance into medical school is the purpose; what he is doing has a purpose.

Most of what is called 'teleology,' and has gone under that label during the centuries since Aristotle, belongs to this concept. Actually, teleology in the Aristotelian sense is a cosmic principle. By 'teleology' is meant the philosophical doctrine that all things in the universe act for some end or purpose. This view characterizes processes as being "purposeful" behavior. Nature is imagined as a mother who skillfully guides the activities of the universe according to her purposes. Imagine the consciousness in mother nature and you have teleology. Part of this notion includes the aspect of "good," i.e., everything in the universe serves some good.

When one speaks of 'the function of a saw' one is referring to the concept of purpose. What we mean is the purpose in the mind of the maker for the saw. Living phenomena were, of course, at one time considered solely as contrivances made by a divine creator, or "Nature" viewed as an artist or craftsman and the 'function' of the organism or the 'function' of a part of an organism meant the purpose of that organism or part in the mind of the creator. This concept was best exemplified by Paley's Natural Theology, published in 1802 in

London. In this work, the purposefulness of each part of various organisms was used to demonstrate the existence of a divine creator.

In earlier centuries, under the Greek world-view in which the universe was considered a macrocosm of man, men often spoke of the function of some item, referring to that item as a means to some end. This was the common way of speaking. However, we can also find the concept of function$_1$ used in earlier centuries, and it is these usages that would constitute the history of the science of physiology, physiology being defined in terms of descriptions of function$_1$.

That function$_3$ is not the primary meaning used by modern physiologists is quite easy to establish from their testimony. Indeed, by an analysis of their technical writing we can show that they use the concept of function$_1$, and thus not "purpose," which is a form of function$_3$. Nagel has put the matter this way:

> Most contemporary biologists certainly do not impute purposes to the organic parts of living things whose functions are investigated; most of them would probably also deny that the means-end relationships discovered in the organization of living creatures are the products of some deliberate plan on the part of a purposeful agent, whether divine or in some other manner supranatural. To be sure, there are biologists who postulate psychic states as concomitants and even as directive forces of all organic behavior. But such biologists are in a minority; and they usually support their views by special considerations that can be distinguished from the facts of functional or teleological dependencies which most biologists do not hesitate to accept.[36]

Although the concept of purpose is not explicitly espoused by scientists today to explain living phenomena, the concept of

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[36]Ernest Nagel, The Structure of Science (New York: Harcourt, Brace and World, 1961), p. 402.

purposefulness or purposiveness is used by some biologists of outstanding reputation. Is this a case where $function_3$ is used in physiology? We would like to show that 'purposefulness' and 'purposiveness' are actually instances of the concept of $function_1$.

Edmund W. Sinnott has written more than any other modern biologist on the concept of purposefulness. An examination of his views will show that he is attempting to reduce the concept of conscious purpose to the concept of a regulated physiological process, i.e., $function_1$. Since from the framework of scientific physiology the concept of purpose is superfluous, the scientifically usable part of purposefulness is the concept of $function_1$ which underlies it. In his book, The Biology of the Spirit, Sinnott is trying to argue "That the insistent tendency among living things for bodily development to reach and maintain, as a norm or goal, an organized living system of a definite kind, and the equally persistent directiveness or goal-seeking that is the essential feature of behavior, and thus finally the basis of all mental activity, are fundamentally the same thing, merely two aspects of the basic regulatory character all living stuff displays."[37] Sinnott is equating conscious or mental purpose with a physiological process, $function_1$. He is making purposefulness derivative from self-regulation.

But Sinnott is also analyzing self-regulation from the viewpoint of conscious purpose. Here he puts the wrong emphasis on

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[37]Edmund W. Sinnott, The Biology of the Spirit (New York: Viking Press, 1955), p. 52.

regulation, i.e., he emphasizes the goal of the process. He views it in terms of a means-end nexus. "Regulation implies something to regulate _to_, a norm or goal."[38] This connotes the concept of purpose. What we hope to show by our explication of 'function' is that regulation implies disturbances to regulate _from_, i.e., disturbances with respect to which a system is regulated. This concept of function_1 will then be reconstructed in terms of amount of variety that can be regulated, thus providing a quantitative concept of regulation, and hence of function. In other words, the concept of a goal-directed process will be explicated in terms of the concept of self-regulation.

We have been endeavoring to show that in the usages of physiologists there are three principal concepts of function. Function_1, the concept of a self-regulated process, is the major concept used by physiologists. Function_2, the mathematical concept of function, is sometimes used by physiologists, but also by other branches of science. Function_3, the teleological concept of function, is rarely used by physiologists; when they do analyze this concept they seem to reduce it to function_1, a self-regulated process.

What the survey of usage throughout this section has established is that in both ordinary language and scientific language there are three principal meanings of the term 'function.' Also we have given some evidence that in the science of physiology, the primary concept used is function_1, i.e., a self-regulated process. A later part of

[38]_Ibid_.

this chapter will substantiate that claim by a detailed study of the writings of important physiologists.

An Analysis of the Usages of 'Function'

This section provides a detailed analysis of the scientific usages of 'function.' We hope to throw the concept of function into clearer light by differentiating it from the other two concepts of function. The one presupposition of our analysis (and of this entire clarification) consists in our choice of a systematic context. We have chosen the contemporary science of physiology as the field in which, and only in which, we are dealing. The concept of function that we endeavor to clarify is that concept used by current scientific physiologists. Now if we assume that current scientific physiologists choose concepts on the basis of their systematic, quantitative, and experimental efficacy, then the concept of function that we endeavor to clarify here will also have these values. What we would like to emphasize is that we are not making a physiological analysis but rather a meta-physiological analysis. Our analysis is in the nature of a logical or semantical activity.

The Categorial Domain

We have seen in the previous section the variety of meanings associated under the heading of 'function.' Now a preliminary step in the clarification of a concept is the determination of the categorial domain, i.e., the determination of the type of entities to which the physiological term 'function' applies.

Traditionally, physiology has been contrasted with anatomy; the former studying functions, the latter studying structures or morphology.

> Thirdly the name ['function'] seems to be used as a name for all the processes ordinarily said to be 'going on in an organ.' This seems to be what is meant when we speak, for example, of the functioning of the kidney, or of renal function. This is what physiologists usually study when they are said to be studying the physiology of the kidney. . . . It is with the third meaning that we shall here be concerned since it is function in this sense that is usually contrasted with structure.[39]

Woodger then points out that physiology, studying functions, i.e., processes, studies them as spatio-temporal events; anatomy however abstracts from the temporal aspect and treats only spatial aspects, e.g., the structure of the heart and circulatory system. We must realize that "the concrete organism is a spatio-temporal structure and that this spatio-temporal structure _is_ the activity itself."[40] We can conclude then that the entities studied by physiology are in the category of "processes," i.e., spatio-temporal structures.

The statements of other physiologists will support this analysis of the categorical domain of 'function.'

A well-known physiologist once spoke of ". . . the campaign of general physiology to discover the workings of the cell, ..."[41] Thus what physiology studies are "workings." To clarify this let us

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[39]J. H. Woodger, _Biological Principles_ (London: Routledge & Kegan Paul, 1967), pp. 327-28.

[40]_Ibid_., p. 330.

[41]Mazia, _op. cit_., p. 77.

refer to an article entitled "Catecholamine Functions." The author gives an explicit statement of what sort of things functions are.

> A dictionary will define function as special activity or purpose. In these pages purposes will be passed over in silence. Thus the discussion will be limited to special activities of the three amines. Established functions or special activities of the catecholamines (CA) are legion, but they will be discussed only with respect to their possible effects on the mechanical activity of smooth muscles.[42]

Thus we see that functions or "workings" are "special activities." Another biologist entitled a section of his textbook: "The Integration of Functions." What sort of things are these functions that are integrated? The sentence following the above heading states, "The integration of the activities of the various parts of the animal body is brought about by two systems: the nervous system and the endocrine system."[43] Thus functions are activities. We see again that the categorial domain is composed of what are generally called 'activities' or 'processes.' Thus when an author says "Let us now proceed to the other phase of kidney function: the secretion, or reabsorption, of substances-- . . ."[44] it is quite easy to see that secretion or reabsorption of substances are activities or processes.

In another sense of 'function,' as in 'The function of a saw is to cut wood,' or 'The function of the handle is to provide a convenient method for carrying,' the categorial domain would be conscious

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[42] J. Axelsson, "Catecholamine Functions," Annual Review of Physiology, XXXIII (1971), p. 1.

[43] Hardin, *op. cit.*, p. 517.

[44] *Ibid.*, p. 569.

intentions or purposes. Since conscious intentions or purposes are found only in beings with a rational faculty and physiology studies beings most of which do not have rational faculties, physiology obviously does not study functions in this sense. One might say that there was an intention in the mind of a divine creator for each function. Physiology, however, does not study the mind of the divine creator; it studies types of living organisms. Thus in no physiological usage does 'function' refer to entities of an intentional sort.

Some authors, attempting to salvage some empirical content from the idea of conscious purpose, have claimed that teleological locutions in biology signify a "means-end nexus."[45] Or, put in another way, the function of some part refers to a utility of that part. Unfortunately, just what sort of entities "means-end nexus" or "utilities" belong to is highly problematic. They could be referring to conscious purposes; in this case the previous comments would apply to them, i.e., physiology does not study conscious purposes. Or they could be referring to the relationship between parts of a scientific explanation or model, i.e., a certain symbol or expression or locution is part of a larger system of symbols, expressions, or locutions. However, if this is the case, we must say that physiology studies systems of symbols, expressions, or locutions; physiology however is not a study of such explanatory patterns or models, it is a study of physical phenomena.

In conclusion then, the functions studied by physiologists belong to the categorial domain of physical processes, not conscious

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[45]Nagel, <u>op. cit</u>., p. 403.

purposes or patterns of explanation. Realization of this fact will render understandable why physiologists are so vociferous in maintaining that 'function' refers to "What x does." The point they are trying to emphasize, albeit in a misleading manner, is that physiology does not study purposes or utilities, it studies physical processes.

In referring to machines or man-made artefacts one sometimes finds the word 'function' applied; and it is in the sense of 'what x does' or 'the working of x.' One speaks for example of 'the function of the carburetor' or 'the function of the handle' and one refers to what these items do, their activity. This is the more general and everyday meaning of 'function.' When this more general usage occurs, the speaker has merely specified the categorial domain, and although it is still vague, he has at least distinguished activity from other concepts such as purpose, etc.

Distinguishing the Three Concepts

The functions studied by physiology are processes. The term 'function' has three usages, as we have shown in the previous section. We can now proceed to a deeper analysis and comparison of these three concepts of function.

The concept of function_1, that referring to a self-regulated process, can be called the 'teleonomic' concept of function. The concept of teleonomy must be distinguished from both 'purpose' and 'teleology.' The concept of teleonomy is an empirical notion. The latter two are non-empirical notions. C. H. Waddington has discussed:

> the most general descriptions of the kind of biological process which have been referred to as 'goal-directed.' The nature of such processes has always been recognized as one of the major problems of theoretical biology. The words to be used for describing them and discussing them are still matters for debate. The earlier expressions 'teleological' and 'finalistic' are usually thought to carry an implication that the end state of the chreod (process) has been fixed by some external agency and that the end state is in some way operative in steering the trajectory towards itself. To avoid such implications I have spoken of such phenomena as 'quasi-finalistic,' and the word 'teleonomic' (introduced I believe in Behavior and Evolution, 1958) has been used as a substitute for teleological.[46]

Ernst Mayr also gives a characterization of 'teleonomy' as follows:

> In order to avoid confusion between two entirely different types of end direction, Pittendrigh has introduced the term teleonomic as a descriptive term for all end-directed systems 'not committed to Aristotelian teleology.'. . . Such a clear cut separation of teleonomy, which deals more broadly with the overall harmony of the organic world is most useful because these two entirely different phenomena have so often been confused with each other.[47]

A teleonomic process, then, is one which is so regulated as to reach or maintain a certain state in spite of changes or fluctuations during that process.

The concept of $function_2$ is referred to as the "mathematical" concept of function. It is found, for example, when the rate or value of one process varies with the rate or value of another process, e.g., 'Sodium level is a function of salt intake.' In the expression 'y is a

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[46]C. H. Waddington, "The Basic Ideas of Biology," in Towards a Theoretical Biology, Vol. I, ed. by C. H. Waddington (Chicago: Aldine Publishing Co., 1968), p. 14.

[47]Ernst Mayr, "Cause and Effect in Biology," in Waddington, op. cit., p. 49.

function of x,' we have x as the independent variable and y as the dependent variable. Changes in y "are dependent upon" changes in x.

The third concept of function, function_3 is called the 'teleological' concept. The function_3 of a part or process is given by stating its role in the whole, which role is essential for life and survival of the organism. It has been recently explicated by some authors as the concept of necessary condition for survival. John Canfield, for example, sets up the following schema:

> A function of I (in S) is to do C <u>means</u> I does C; and if, <u>ceteris paribus</u>, C were not done in an S, then the probability of that S surviving or having descendants would be smaller than the probability of an S in which C is done surviving or having descendants.[48]

Having outlined the three concepts of function, let me now compare and contrast them. What we would like to show first is the relationship between function_2 and function_3. Then the relationship between function_2 and function_1.

Consider this illustration of function : 'The production of cellular material is a function of photosynthesis' (y is a function of x). Notice that we can convert this statement so it reads 'A function of photosynthesis is production of cellular material' (A function of x is y). This latter statement can be taken as an illustration of function_3. Is there a deeper relation between the two than mere paraphrasing?

Consider the empirical tests that are used to establish the existence of functions. The verificatory method behind function_2 is

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[48]John Canfield, "Teleological Explanation in Biology," <u>British Journal for the Philosophy of Science</u>, XIV (1964), 292.

this: If you vary x over a range of values, then there should be some related pattern of variation in y. For example, if you increase the intake of salt then there should be an increase in the sodium level; if so, then we say sodium level is a function of salt intake. Notice that the proportionality between the variation of x and y depends upon the context. First, the proportionality may be direct, as in the case of the volume and temperature of a gas, or inverse, as in the case of the volume and pressure of a gas, or it may be any other mathematically-stated relationship, e.g., y may vary as the square of x, etc. Secondly, there is some theoretical context which provides theoretical direction for comparing y and x, and not y and some other factor. It might be something as simple as that y and x are the same substance and occur in the same system, such as the above example of salt and sodium, or it might be a more complicated theoretical mechanism which links two different factors, e.g., suicide rate and cohesiveness of society. Thirdly, there are boundary conditions which determine which factors are irrelevant in any situation.

Given this theoretical framework, the basic idea is this: y, the dependent variable, is determined by the independent variable (or variables). For the values of the independent variable (or variables), there is a value of y. Otherwise y is not a $function_2$ of x.

Now how do we establish that the $function_3$ of x is y? In an analogous manner to one type of $function_2$. First let us take the idea of necessary condition. 'The $function_3$ of the heart in mammals is to pump blood' means that with a heart there is pumping of blood and without a heart there is no pumping of blood. Here we really have the concept of $function_2$, except that we have a range of variation of only two values for x and y. Suppose '0' means 'absent' and '1' means 'present.' Then if the heart is present, (has the value 1), pumping blood is present (has the value 1). And if the heart is absent (has the value 0) then pumping blood is absent (has the value 0). Thus the heart is a necessary condition for pumping blood; with the heart blood is pumped, without it no blood is pumped. (Obviously all the other conditions necessary for being a living organism would have to be present.) This $function_2$ has of course only the two values 0 and 1, or 'yes' and 'no' and is really just a qualitative approach. However it was characteristic of biology until recent times that it had a strictly qualitative approach and so the concept of $function_3$ is really just a two-valued or qualitative instance of a $function_2$, varying in direct proportionality.

Those who would define 'the $function_3$ of x is y' to mean that x does y and y is a necessary condition for survival would also find that this definition is explicable as a two-valued $function_2$. If y occurs the organism survives, without y occurring the organism does not survive.

Now one might propose that as the pumping of blood varies, so does the survival rate vary; and a multivalued $function_2$ would be possible. This has not in fact been proposed by physiologists, mainly because it assumes a quantitative concept of $function_1$, which is not at present available in physiology and which this dissertation attempts to construct. (One could not take a simple physical rate such as flow velocity of blood and correlate it with survival rate since obviously there is a relative optimum for flow velocity of blood. In other words just increasing the blood velocity would only injure the organism, not increase its chances of survival. And similarly for other rates and correlations.) We might add also that a quantitative concept of survival has not yet been achieved either.

More evidence of the fact that function_3 is really just a two-valued instance of function_2 is found by considering the "ablation experiments" which were used in the 19th and early 20th century in physiology. These experiments are no longer recognized as of much value because they present an over-simplified picture. In an ablation experiment, a part was removed from a living organism and then the organism was observed. Whatever activities of the organism ceased upon removal of the part were considered to be the "function_3" of that part. If upon removal of the optic nerve, vision ceased, then the conclusion was drawn that the function_3 of the optic nerve is to aid in vision. Again note that this is our two-valued function_2. If optic nerve present (1), vision present (1); if optic nerve absent (0), vision absent (0). It is this two-valued function_2 which constitutes the basis of the concept of function_3.

A function_1 is also related to the concept of function_2. A physiological system is a process whose behavior is a function_2 of the environmental disturbances and controlled compensations. In the general mathematical (or logical) sense it can be viewed as a function_2. Also, the component processes which make up the parts of the physiological system can be viewed as $functions_2$, i.e., the controller value is a function of the input, etc. Earlier in the history of physiology, physiologists who were known as "vitalists" maintained that self-regulatory activities did not act in the pattern of a $function_2$, in fact they violated the usual deterministic processes. However, as our explication will show, self-regulation is achieved not by violating deterministic $functions_2$ but rather it is achieved by combining them into a system that enables them to counteract each other.

We have shown the relationships between the three concepts of function for the purpose of setting the concept of $function_1$ in a clearer light.

The Grammar of 'Function of'

An ambiguity has existed in the literature on 'function,' which holds a key to a very penetrating analysis of the concepts of function. The ambiguity is in the grammar of the word 'of' in the locutions 'function of.'

There are two different usages of the expression 'of' in general. The first we will call 'instantial.' Locutions such as 'the city of Rome' or 'that fool of a husband' are illustrations of this usage of 'x of y' where y is an instance of x, i.e., y is an x, for example, 'Rome is a city,' 'my husband is a fool.' In these cases we are saying that y is a member of the class x. The other and more common usage we will call the 'relational' usage. Thus a 'man of ability,' 'the plays of Shakespeare' are illustrations of this basic usage, 'x of y,' where y is not an instance of x, but is related in some way to x, e.g., 'the man has ability,' 'the plays have been written by Shakespeare.'

In the instantial usage of 'x of y,' we are saying y _is_ x, y is an instance of x, or y is in apposition to x. This usage can be determined by a simple comma-replacement test. If in an occurrence of 'x of y' one can replace the word 'of' by a comma without loss of meaning then this occurrence contains an instantial usage. Thus 'the city of Rome' could be expressed as 'the city, Rome' without loss of meaning. Another example of words connected instantially by 'of' would be 'the color of red of the ball.' This could be expressed as 'the color, red, of the ball.' The last 'of' in this phrase is, of course, not an instantial usage but a relational one.

These usages of 'of' can be found in function locutions. In the case of the instantial usage, we find the locution 'the function of respiration.' In the relational usage we find 'the function of the heart.' The former case implies that respiration _is_ a function, the latter case, a relational usage, uses a noun in the place of y and denotes ownership or possession: the heart possesses a function. Or put another way, the function has the attribute of "belonging to the heart."

Now the claim we are advancing is that the concept of function_1 involves only instantial usages of 'of'; the concept of function_3 involves only relational usages of 'of.' 'The function_1 of respiration' can be expressed as 'the function_1, respiration'; it implies that respiration is a function_1. 'The function_3 of the heart' on the other hand, cannot be expressed as 'the $function_3$, heart.' Rather, it implies that the function has as an attribute that it belongs to the heart. In 'the $function_1$ of respiration' we are told what respiration is, and we are given an instance of a $function_1$; in 'the $function_3$ of the heart' we are not told what a heart is, and we are not given an instance of a function. It takes a more complete statement to give the $function_3$, e.g., 'The function of the heart <u>is</u> to pump blood.'

Now what this shows us immediately is that since the two usages of 'of' appear grammatically the same, yet we can clearly distinguish them by examples, then we must have two distinct concepts of function, so that we can distinguish the two classes of usages of 'function of.'

More deeply, what this means is that $function_3$ locutions must have an object, some substance which possesses the function whereas $function_1$ locutions do not need such a substance. In other words, $function_3$ locutions presuppose the old metaphysics of a substance and its attributes. This is best exemplified by the antithesis of structure and function in biology as a whole. The $function_1$ locutions, however, assume that the function (process) is all that exists. In 19th century physics it was thought that to have "waves" required a substance or medium which did the waving; eventually the ontologically fundamental character of waves (fields) was accepted with no necessity for postulating a material medium. In psychology, too, it was always assumed that psychological attributes needed a substance, e.g., a soul or personality or ego, in which to inhere. However, later psychologists such as William James began to do psychology without postulating this enduring static substratum; the psychological functions, i.e., processes, were taken as ontologically primitive. Now in physiology a comparable change has occurred. Physiologists previously assumed that any function, i.e., process, must have its anatomical substratum, i.e., that which did the functioning. Now, however, physiologists began to make functions_1 ontologically primitive, and to study functions_1 as such, i.e., ignoring the anatomical substratum.

Let us put the point this way: 'The function_3 of the heart is to pump blood' can be expressed as a dyadic relation, F(h,p) where h is an object and p is the activity of that object. Function_1 locutions have no specific relation which they invoke. 'The function_1 of respiration is well-studied by modern physiologists' is expressing the relation S, "being well-studied by" and is expressed 'S(F,r)' where F is an activity and r is a person or group of persons. 'The function_1 of respiration consists of oxygen exchange' is an example of the relation "consisting of" expressed by 'D(F,w)' where F is the activity and w denotes its defining characteristics.

Thus we can meaningfully say 'y is a function_1' but it is meaningless to say 'p is the function_3.' We normally must say 'p is the function_3 <u>of h</u>.' Thus function_3 is wedded to the substance-attribute assumption whereas function_1 is not. And thus the expression 'The function of h is p' would be restricted to the concept of function_3. In fact this is the case in biological usages.

The locutions where this ambiguity appears most strongly are locutions such as 'the function of photosynthesis,' i.e., 'the function of y' where 'y' is a process. Here one can mean two things: Either 'the $function_1$ of photosynthesis' or 'the $function_3$ of photosynthesis.' There would be some difficulty in deciding which meaning was intended. Usually, if what follows this locution is definitive, i.e., 'the function of photosynthesis is production of cellular material,' then $function_1$ is intended, i.e., 'The function, photosynthesis, consists of production of cellular material.' If it is not meant definitively, then it means that the $function_3$ of photosynthesis is the production of cellular material. If one says either 'the $function_1$ of photosynthesis has been well-studied' or 'the $function_3$ of photosynthesis has been well-studied,' there is not direct way to distinguish these two cases. One can only substitute either 'process' e.g., 'the process of photosynthesis has been well-studied' or 'purpose' or 'utility,' e.g., 'the purpose or utility of photosynthesis has been well-studied' and then determine which fits the context more closely.

This ambiguity of the term 'of' was long ago pointed out by G. E. Moore in his article "The Refutation of Idealism."[49] There Moore pointed out that though 'a blue sensation' and 'a sensation of blue' appear synonymous, just as 'a glass mirror' and a 'mirror of glass,' or a 'blue bead' and a 'bead of blue' are synonymous, in fact the first two locutions are not synonymous. Idealists rely upon the synonymity to establish their position that "to be is to be perceived." Upon close analysis, 'a blue sensation' is obviously nonsense, since

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[49]G. E. Moore, "The Refutation of Idealism," in <u>Philosophical Studies</u> (New York: Humanities Press, 1922).

sensations, as mental entities, have no color; a 'sensation of blue' however, upon analysis can be seen to have three parts: it involves consciousness, blue, and a relation between them. Moore thus attempted to bolster a realistic epistemology. Now we have tried to show that in the case of 'function' the same distinction holds. The function of photosynthesis could refer either to the process photosynthesis, or to the role of photosynthesis in the organism as a whole. In the former we have function_1, in the latter case we have function_3.

Other Recent Analyses

The choice of an explicandum, as we have taken pains to point out in this chapter, is an important phase of an explication. In the next few pages the explicanda chosen by recent philosophers of science who analyze the concept of function will be discussed, and its relationship to their explicata will be examined carefully. For the most part recent philosophers of science have used the teleological concept, function_3, in their explicandum. Some however have failed to adequately clarify the pre-systematic term 'function' and their explicandum involves a mixture of function_3 and function_1. It must also be remembered that these explications are not primarily directed toward explicating the concept of function, but rather, they are directed toward explicating function statements, analyses, and explications. Usually, though, somewhere in this process some explication of the concept of function itself is offered.

The concept of a self-regulated activity was used as an explicatum by Rosenblueth, Wiener, and Bigelow in their 1943 article.[50] In this article the authors attempted to explicate 'purpose' and 'purposeful behavior' in terms of a self-regulating negative-feedback system. It was unfortunate that they chose 'purposeful behavior' as their explicandum. For while the negative-feedback approach was well-done and produced a clear explicatum, it was not relevant to the explicandum. Israel Scheffler capitalized on this to raise a number of counter-examples to the claim that 'purpose' could be explicated in terms of negative feedback.[51]

A few years later G. Sommerhof proposed a formal model of "directive correlation."[52] Sommerhof, like Rosenblueth, Wiener, and Bigelow before him, intended his model to explicate the notion of purposive behavior. This explicandum was taken in a wide sense and included a diverse range of purposive phenomena on the biological, psychological and sociological level. Later philosophers of science, namely Ernest Nagel, R. B. Braithwaite, Morton Beckner, and W. Ross Ashby all used Sommerhof's work, making only minor revisions in it. All of these later authors used as an explicandum the idea of teleological explanation; and used Sommerhof's model as part of their explicatum of this explicandum.

In summary then, those authors who did explicitly discuss the teleonomic concept of function and who even used a formal model of it

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[50]Arturo Rosenblueth, Norbert Wiener, Julian Bigelow, "Behavior, Purpose and Teleology," Philosophy of Science, X (1943), 18-24.

[51]Israel Scheffler, "Thoughts on Teleology," British Journal of Philosophy of Science, IX (1959), 265-84.

[52]G. Sommerhof, Analytical Biology (London: Oxford University Press, 1950).

as an explicatum can be seen to have failed to distinguish in their explicandum between function_1 and function_3. In effect they were expecting a formal model of a teleonomic concept to provide an explication for the teleological concept of function. It is no wonder that these attempts to explicate 'purpose' in terms of self-regulating machines have been unacceptable to a large group of philosophers.

The other philosophers of science who discuss 'function' have chosen function_3, the teleological concept, as their explicandum. All of the more recent work has dealt with this teleological concept of function, as it is found (claim these philosophers!) in biology. The two major explicata have been either the concept of necessary condition or of survival.

A well-known exponent of this view that 'function' means necessary condition is Ernest Nagel.[53] Nagel makes no distinction between teleological (or functional) statements, teleological analysis (functional analysis), and teleological explanations (functional explanations). According to Nagel, they are all telescoped arguments. He takes as an example:

> The function of chlorophyll in plants is to enable plants to perform photosynthesis

and claims that this can be rendered as:

> When supplied with water, carbon dioxide, and sunlight, plants produce starch; if plants have no chlorophyll, even though they have water, carbon dioxide, and sunlight, they do not manufacture starch; hence plants contain chlorophyll.

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[53]Nagel, op. cit., p. 403.

In other words, 'the function of x in z is y' means z does y; z without x does not do y. Thus z has x. Thus we have:

the function of x in z is y = i) z does y

ii) z does y $\supset$ z has x

iii) z has x

Thus on Nagel's definition, 'the function of x is y' means what x does, its effect, that is a necessary condition for y. The first statement above, on Nagel's view "appears to assert nothing that is not asserted by 'Plants perform photosynthesis only if they contain chlorophyll,' or alternatively by 'A necessary condition for the occurrence of photosynthesis in plants is the presence of chlorophyll.'"[54] Thus we have the concept of function_3.

What evidence does Nagel give for his claim that this is the meaning of 'function' used by biologists and physiologists? Though he claims that he will "argue" that his reformulation of functional statements is correct, nowhere does he present any direct evidence. No examples of usages in the literature of biology or physiology, no definitions given by biologists or physiologists are cited. The real reason for Nagel's definition lies in his desire to mold function statements into the deductive model of explanation. Notice that in the third statement above, the conclusion, i.e., the explandum, of the functional explanation is the statement of the presence of chlorophyll in plants. Now it seems clear that physiologists are not interested in explaining the presence of particular items, rather

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[54] Ibid., p. 405.

they are interested in describing the processes involving these items. The physiological scientist is not interested in being able to demonstrate that plants have chlorophyll; he knows this. Rather, as a physiologist he begins with this fact and tries to describe how chlorophyll operates, i.e., functions_1, in photosynthesis in plants.

As a conclusive argument that Nagel has not captured the meaning of 'function' with the concept of necessary condition, we offer the following evidence. Namely, that causal and temporal analyses or explanations also have the same definiens which Nagel claims is proper to functional analyses. When we say,

The heartbeat causes the blood to circulate

we can reformulate this as,

If there is no heartbeat there is no circulation of blood

or

The blood circulates only if the heart beats.

Thus 'x causes y' means y only if x, i.e., x is a necessary condition for y. Thus we can explain the presence of the heartbeat, i.e., because there is circulation and there is circulation only if there is a heartbeat. The above causal analysis would, of course, have to be put into the context in which all the other conditions in the organism were properly satisfied, just as in the case of the functional analysis. The point to be noted is that in functional and causal analyses alike, the notion of necessary condition is found. Thus it is not only the idea of necessary condition that constitutes the meaning of 'function.' A functional analysis is used in physiology because it employes the concept of $function_1$, just as temporal analysis is so-called because it employs the idea of temporal precedence, or causal analysis employs the idea of causal connexion.

What Nagel has done, it seems, is mis-apply the idea of necessary condition, which is employed in the concept of explanation, to the concept of function, through confusing these two distinct ideas in the term 'functional explanation.' Because of this pre-occupation with the deductive model, he has not given a correct definition of 'function,' and he has failed to emphasize the distinctive character of a functional analysis, i.e., its use of $function_1$. The reason Nagel formulates the definition he does of 'function' is so that it will illustrate the deductive model. (Not that we have any objections to the deductive model here, only that Nagel has not brought out the "functional" part of functional explanations.) He says,

> The above teleological account of chlorophyll, in its expanded form, is simply an illustration of an explanation that conforms to the deductive model, and contains no locution distinctive of teleological statements.[55]

This seems to be the only "argument" given to support his analysis of 'function.'

Other philosophers of science who treat functional analysis, e.g., Morton Beckner, Arthur Pap, Hugh Lehman, John Canfield, Michael Ruse, and Carl Hempel, fail to separate the analysis of the concept of function from the analysis of functional explanation or functional analysis. They all conclude, with minor variations, that 'the

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[55] Ibid.

function of x in z is y' means x is a necessary condition for y occurring and y is a necessary condition for z surviving.

Hempel does make some attempt to treat the concept of function in the following way. In the statement, 'The heartbeat in vertebrates has the function of circulating blood through the organism,' what does 'function' mean, he asks. It cannot mean "effect," is Hempel's first conclusion; otherwise 'The heartbeat has the effect of producing heart sounds' would be equivalent to 'The heartbeat has the function of producing heart sounds.' Hempel then elaborates an explication of the following sort: 'The function of x is y' is defined as: x does y and y ensures the satisfaction of certain conditions which are necessary for the proper working of the organism (provided the background conditions for the organism are satisfied). More precisely, Hempel puts it this way: That item i functions in system or organism S means that i occurs in S under certain conditions C_i and C_e (internal and external boundary states) and i "has effects which satisfy some 'need' or 'functional requirement' of S, i.e., a condition which is necessary for the system's remaining in adequate or effective, or proper, working order."[56]

Hempel's argument, that 'the function of x is y' cannot mean x does y, is the argument used most often by those who oppose the view that function_1 is the concept of function used in biology and physiology. Hempel's argument is that no physiologist would say 'the function of the heartbeat is to produce heart sounds' because heart sounds are "accidental," they satisfy no real biological need of the organism. This

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[56]Hempel, op. cit., p. 306.

argument, it seems, fails to capture the meaning of 'function.' One circularity found in Hempel's reasoning is that his definiens contains the expression 'functional requirement' and 'proper working,' which either refer to $function_3$ and thus the definition is circular, or may refer to $function_1$, and thus help to establish our point, that $function_1$ is the principal meaning of 'function' in physiology. Hugh Lehman also commits the same fallacy. He defines 'a function of x is y' as: x causes y and y "is a necessary condition for the proper functioning of the organism."[57] It seems to us that the question of the physiologist is, how describe the proper functioning? This is a demand for a description of the $function_1$ in that organ or organism or system.

The existence of this circularity in these definitions thus points out that they have not yet captured the meaning of 'function.' To define 'the function of x is y' as: x does y and y satisfies a functional requirement, still leaves us with the original question, what is the meaning of 'function,' i.e., 'functional requirement' in this case?

Other philosophers, notably John Canfield, have replaced Hempel's functional requirement by the idea of the survival of the organism or species. Thus 'the function of x is y in z' means x does y and y is a necessary condition for the survival of z. All this explication does, however, is define 'function' in terms of survival of the individual and the species; and this concept of survival of

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[57]Hugh Lehman, "Functional Explanation in Biology," Philosophy of Science, XXXII (1965), 12.

the species is even more problematic. In fact the chief reason why function$_3$, defined in terms of necessary condition for survival, is not the concept of function used by physiologists can be shown by exhibiting the conceptual independence of physiology from evolutionary ideas such as survival. The first point to make is then that even if 'function' was defined in terms of survival this would provide no clarification or precision of the concept of function. At first biologists defined survival in terms of fitness. Then when the circularity of this became apparent they defined it in terms of differential reproduction. Still later it was defined in terms of adaptation. The present status of the concept is in no way improved. Stebbins summarizes it this way: "Unfortunately, however, the determination of the adaptive character of many types of differences between organisms is one of the most difficult problems in biology."[58] Thus 'survival' and its part in the theory of evolution, are quite problematic.

A second point we would like to make is that physiologists are not working in the theoretical structure of the theory of evolution, along with its notion of survival. As a historical point, physiologists were using function$_3$ concepts, teleology, long before the theory of evolution became the accepted biological paradigm. On the whole, it seems as if modern physiology and the concept of function which it employs, has no conceptual connection with evolution theory, except as a heuristic aid. "In retrospect, we can see that though the impact

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[58]G. L. Stebbins, Jr., Variation and Evolution in Plants New York: Columbia University Press, 1950), p. 118.

of evolution upon physiology was neither as revolutionary nor as pervasive as upon some other biological sciences, subtle but nevertheless historically interesting effects may be traced."[59]

The impact of evolution theory was of a heuristic nature. The above quotation refers to 19th century evolution theory which had an aspect no longer in use today in evolution theory, viz., Lamarckism. The debate in evolution theory at the time was over the question whether use determines structure (Lamarckism) or structure determines use. An English scientist, C. J. Romanes, assumed that use or function antedated structure with regard to the formation of specific nerve trunks. There must have been some rudimentary irritability present, i.e., some rudimentary nervous characteristics of tissue, which, with use, evolved into specialized tissue for nervous functions only. "And I think it follows deductively from the general theory of evolution that reflex action ought to be present before the lines in which it flows are sufficiently differentiated to become distinguishable as nerves."[60] As a result, Romanes' assumption provided the motivation for him to study the nervous tissue of the Medusa and he described accurately its function_1, i.e., he made important contributions to the physiology of the nerves.

Recent analyses of 'function' in physiology show an irrelevance to the science of physiology. The main deficiency results from choosing teleological function or a broad concept of function including both the

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[59]Richard D. French, "Darwin and the Physiologists," Journal of the History of Biology, III (1970), 273.

[60]G. J. Romanes, quoted in ibid., p. 261.

teleonomic and teleological concepts as the explicandum. Most authors seem to assume that $function_3$ is the concept of function used in physiology and proceed to explicate it without adequate preliminary clarification. The purpose of this chapter is to provide the much needed thorough clarification of the concept of function.

The Historical Development of '$Function_1$'

In this section the historical development of the concept of $function_1$ will be briefly traced. We are using historical material for two reasons. First of all, one of the claims of this entire essay is that $function_1$ is in fact the meaning of 'function' in the science of physiology. This is a semantic claim and we hope to bolster it by the etymological and conceptual evidence contained in this section. Through a study of the development of the concept of $function_1$, we hope to show in what sense it can be called the physiological concept of function. Also we would like to show that the concept of a self-regulated process was implicitly used in early biology and medicine.

In the second place, a discussion of historical examples will serve to further sharpen our intuitions regarding the meaning of 'function' we have in mind, and which will be the explicandum for the construction of a quantitative explicatum.

Physiology has gone through a development similar to that which physics went through. In the 20th century the basic concepts of physics were radically altered. Classical or Newtonian physics has been replaced by quantum and relativistic physics. In physiology too, classical or teleological physiology has been replaced by molecular and regulatory physiology. The theoretical framework of classical physiology has four characteristics. First, its most fundamental explanatory category was that of the concept of teleology. Secondly, its fundamental categories, including the most fundamental one, teleology, were qualitative as opposed to quantitative. Thirdly, classical physiology was tied to medicine, its goals were essentially pragmatic and therapeutic. Fourthly, classical physiology was essentially tied to anatomy. Contemporary physiology, on the other hand, has the following characteristics. First its most fundamental explanatory category is that of teleonomy, i.e., self-regulation. Secondly, its fundamental categories, including its most fundamental one, teleonomy, are quantitative. Thirdly, contemporary physiology is an area of pure research in its own right, no longer a handmaiden for medicine. Fourthly, contemporary physiology is essentially tied to biochemistry and biophysics.

Just as many writers and most laymen ignorantly think of classical Newtonian physics as being the conceptual foundation of physics, so too many mistakenly think of classical physiology as constituting the conceptual foundation of physiology. This is true of most philosophers of science who are trying to explicate concepts of purpose and teleology.

There are some differences however between the concepts of classical physics and those of classical physiology. The fundamental categories of classical physics were quantitative, e.g., force and gravitation, whereas the concepts of classical physiology were qualitative. Also, classical physics was a fundamental science, it was not based upon any other discipline, whereas classical physiology was essentially tied to anatomy. Classical physics was an area of pure research too. Classical physiology on the other hand has always remained a handmaiden of the medical art. Physiologists always came from the medical schools.

In all their attempts to bring out the meaning of 'function' as it is used in biology and physiology, philosophers of science have neglected to do field work. These authors have given their analysis of function statements based upon a few stereotyped statements of classical physiology, such as 'The function of the heart is to pump blood.' Rarely have they offered as evidence the actual usages of contemporary physiologists. We hope to show through an examination of usages of the term 'function' and the development of these usages over time, just what its meaning in fact is. This section consists of a study of these usages of 'function.' It follows Wittgenstein's maxim: "Don't think, but look." The meaning of a word will reveal itself over many cases of usage.

Since physiology is defined as the science of function, in giving this historical background we will be tracing the origins of contemporary physiology. The American Physiological Society published a survey of the science of physiology in 1958. Physiology was characterized as a branch of biology that studied function. "Within biology, the study of the dynamic or the active events in living beings is the subject matter of physiology."[61] That this is referring to function$_1$

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[61] R. W. Gerard, *Mirror to Physiology* (Washington, D.C.: American Physiological Society, 1958), p. 1.

is shown by their statement that "Physiology is thus functional biology--using the word function in its scientific rather than its pragmatic connotation. To those seeking to learn how organisms function, how life goes on, physiological science provides an approach which cuts across the lines of traditional biological disciplines."[62] Thus this historical treatment will be done from the point of view of tracing the origins of the contemporary concept of function_1, self-regulated biochemical processes.

This has not always been the concept of function used by biologists and physiologists. In the following pages we hope to show the changes and permanence in the conceptual framework of physiology. Physiological theories have changed, and we are not attempting to determine which one is the "correct" theoretical framework. We will accept the fact that the correct framework is the one currently accepted as correct by physiologists. "Physiology . . . has several definitions and those who belong to it by profession will inevitably characterize it."[63]

Pre-20th Century

In Greek biology and medicine, two distinct concepts of function can be found. The first is the teleonomic concept, function_1, i.e., a self-regulated process. The second is the teleological concept, function_3, i.e., an activity that is a necessary condition for survival or purpose or utility. Hippocrates used a fairly clear concept of function_1.

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[62] Ibid., p. 2.

[63] Ibid., p. 30.

However Aristotle and Galen after him, introduced $function_3$ and it is this concept of function which was passed down through their tradition and dominated classical physiology for millenia.

The work of Hippocrates (460-377 B.C.) was imbedded in the concept of the natural healing power of the body, called the "vis medicatrix naturae." According to this principle, the body, i.e., "nature," contained within itself the ability to restore itself in the face of disorders or disease. "But there was a natural tendency in the organism to heal itself; no sooner did it find the environment acting prejudicially upon it then it in turn reacted. Finding its humours in a state of dyscrasia [uneven mixture], it proceeded to bring these back to the proper proportion."[64] Through a wide range of disturbances, the body, if given the opportunity (and this was the physician's task), would restore itself to normal. This basic idea is actually the idea of a self-regulated system. It is the concept called "teleonomy" in the previous sections. There we spoke of teleonomic, i.e., self-regulated biochemical processes as constituting the concept of $function_1$. Although Hippocrates lacked the correct biochemical concepts, he did clearly express the concept of self-regulation. Hippocrates spoke in terms of the "four humors" theory. For him the maintenance of a proper proportion of blood, phlegm, black bile, and yellow bile constituted the healthy state of the animal. Hippocrates has said that "Medicine in fact is subtraction and addition; subtraction of what is in

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[64]Arthur J. Brock, Greek Medicine (New York: E. P. Dutton & Co., 1929), p. 10.

excess, addition of what is wanting."[65] This of course is a description of regulatory compensation or what is today called "negative feedback." "State the ancient hypotheses a little differently, give them a slight push, see them from another angle, and they will often parallel modern conceptions. . . . This reflection applies to many of the Hippocratic concepts."[66] Especially, as we have tried to show, does this apply to Hippocrates' principle of nature as a self-recovering system. "Today more universally than ever, if not more profoundly, we realize that the power of an organism to heal or restore itself is one of the universal marks dividing all living organisms--plants, animals, and man--from the inorganic world."[67]

It is with Aristotle (384-322 B.C.) that the concept of function$_3$, teleology, began to play a predominate role in biology (including physiology and medicine). Aristotle's teleological dictum has two forms: 'nature makes nothing without a purpose' and 'Nature does nothing in vain.' This latter principle seems to be what those philosophers of science have in mind who equate 'function' with necessary condition for survival or living. 'Nothing in vain' would mean nothing that is not useful or necessary for survival or living. The former principle would be an expression of the concept of purpose or conscious intent. Aristotle invoked the concept of teleology as the theoretical framework in which to interpret living phenomena. Although modern philosophers of

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[65]Hippocrates, Breaths, par. 1.

[66]Henry Osborn Taylor, Greek Biology and Medicine (Boston: Marshall Jones Co., 1922), p. 74.

[67]Ibid., p. 138.

science interpret the teleological concept of function as referring to an activity which is a necessary condition in the organism, it seems that Aristotle meant for teleology to refer to an entirely different categorial domain, viz., the domain of conscious intentions. Aristotle's teleological interpretations were always anthropomorphic, using either human psychological or sociological terms. "Now we see that the things which move the animal are intellect, imagination, purpose, wish and appetite. Now all these can be referred to mind and desire."[68] Aristotle also states that

> the constitution of an animal must be regarded as resembling that of a well-governed city-state. For when order is once established in a city there is not need of a special ruler with arbitrary powers to be present at every activity, but each individual performs his own task as he is ordered and one act succeeds another because of custom. And in the animals the same process [Gk. 'thing'] goes on because of nature and because each part of them, since they are so constituted, is naturally suited to perform its own function [Gk. 'ergon']; so that there is no need of soul in each part, but since it is situated in a central origin of authority over the body, the other parts live by their structural attachment to it and perform their own functions [Gk. 'erga'] in the course of nature.[69]

Aristotle's basic theory is then that the soul, a kind of unmoved mover, moves the other parts to perform their activities. The soul or vital principle, moves these parts by means of mind and desire. Thus the teleology of Aristotle invokes the concept of conscious purpose.

We would like to point out that Aristotle also has a very vague form of function$_1$, i.e., the concept of a special process. And while

[68]Aristotle, Movement of Animals, 700b 17-19.

[69]Ibid., 703a 29-703b2.

Aristotle used the terms 'heneka' and 'telos' for purpose, he was always careful to use 'ergon' for process, i.e., the very vague form of $function_1$. The translators translate 'ergon' as 'function' and 'heneka' or 'telos' as 'purpose' or 'goal.' Thus in the quotation in the above paragraph, the activity of the part is translated as 'function.' The 'ergon' was the special activity of some part or organism. It was what x did as x. The word 'ergon' and its meaning have come into the English language in the word 'organ.' In Aristotle's writings the organ (Gk. 'organon') was the thing, the structure, in which the ergon, activity, was located. 'Organon' is also translated as 'tool,' i.e., the thing which performs the action (ergon). Thus the idea of a tool as a means to an end, as something made for a purpose is also found in the word 'organon.' Thus the importance of the organs of the body for physiology has been that they are the places where the processes (erga) take place. Often organs such as the heart, are defined in terms of their activity.

So it is quite clear, it seems, that for Aristotle there existed a very vague concept of $function_1$, for which he used the term 'ergon.' Aristotle was aware of the actual processes going on in living things and he described them as best he could. This is not to say that he conceived of them as self-regulated, as physiologists do today, or that he explained them as they are explained today. He was quite different from modern physiologists in that his descriptions of functions were not quantitative. His lack of a mathematical description of the patterns of processes was what kept his use of the concept of $function_1$ so rudimentary. It seems that he let the anthropomorphic models of human purposes steer him in a direction which took him away from the recognition of self-regulated processes.

That Aristotle made a distinction between 'purpose' and 'function' is often ignored by those who discusss Aristotle's biological theories. John Herman Randall, Jr., in his work of Aristotle has committed this error. Randall notes that in the Parts of Animals, Aristotle discusses the fact that bile is a waste product; it, according to Randall, "performs no function." What Randall means is that it serves no purpose. Aristotle's text on this point is translated by Randall as "But while some things serve a function, many others are present of necessity because of these things."[70] The Greek word that Randall translates as 'function' is 'heneka,' not 'ergon,' and should have been translated 'purpose.' A. L. Peck, who translated the Parts of Animals for the Loeb Classical Library, did translate 'heneka' correctly as 'purpose' in this sentence.[71]

For Aristotle then, the concept of purpose was distinct from the concept of function. The concept of function was very vague, however, and Aristotle did not use it as his fundamental explanatory category. Rather he used the concept of purpose and this has been accepted by later generations as the traditional Aristotelian viewpoint.

The physician Galen (131-201 A.D.) also used the two concepts of function and purpose in his writings; and, like Aristotle, the

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[70]John Herman Randall, Jr., Aristotle (New York: Columbia University Press, 1960), p. 238.

[71]Aristotle, Parts of Animals, trans. A. L. Peck (Cambridge, Mass.: Harvard University Press, 1961), p. 171.

concept of function$_3$, the teleological concept, received overwhelming emphasis. It was in one of his most famous works, On the Utility of Parts, that Galen expressed the teleological views for which he was so well-known. "Unquestionably Galen's over-aptness at finding a purpose and use for every organ--a use and purpose which made the organ what it was--contributed to his dominance in the centuries after him."[72] That Galen also followed Aristotle in using human models or anthropomorphic attributes was brought out by Taylor, who says that "The ancients, Galen, for example, were more addicted to personification than ourselves, who have substituted processes for persons, thus using a more commonplace word [process] to express what is still mysterious."[73] Thus the teleological concept of function, in the sense of conscious purposes predominated in Galen.

That Galen also used a concept of function which referred to physiological activity is shown by examining two of his major theoretical points: the idea of faculties, and the dependency of function on structure. The concept of function$_1$ used by Galen is admittedly vague and he was only vaguely aware of the idea of self-regulation; but he did distinguish this idea from purpose. In his work On the Natural Faculties Galen discusses the faculties of living organisms. "The 'faculties' or abilities for attraction, selection, alteration, expulsion, and retention of materials were hypothetical categories that helped Galen to picture the processes by which animals kept

[72]Taylor, op. cit., p. 104.

[73]Ibid., p. 111.

themselves in repair and enhanced their survival."[74] This idea of "faculties" was also found in Aristotle, although Galen gave a more detailed treatment. These "faculties" were supports for activities by which the organism would maintain itself in the face of a changing environment, thus supports for functions_1.

In another work, the Parts Affected, Galen was dealing with the relationship between structure and function. Here Galen ". . . sets forth the importance of reaching a clear decision as to the part affected and the nature of the trouble, and proceeds on the principle that there can be no disturbance in the function without an affection of the part."[75] Here again Galen is using the idea of special activity, i.e., a very vague function_1. Thus Galen, like Aristotle, used both concepts of function, although function_3 dominated.

For the next 1200 years the teaching of Hippocrates, Aristotle, and Galen was passed down through successive generations. The concepts they used were accepted by generation after generation of scientists and physicians. Change and development only occurred when men began to reject the authoritarian dominance of the writings of Greek biology and medicine.

We thus can see that in Greek biology and medicine the basic characteristics of classical physiology were evident. The teleological viewpoint, championed especially by Aristotle and Galen, was the fundamental explanatory framework. Anatomy, such as it was, furnished the

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[74] E. F. Adolph, "Early Concepts of Physiological Regulation," Physiological Review, XLI (1961), p. 742.

[75] Taylor, op. cit., pp. 109-110.

objects to which functions were attributed. There was no use of quantitative methods. And the study of functions was used for the purpose of aiding physicians in their diagnoses and treatments. The idea of self-regulation was quite clearly used by Hippocrates, as we have seen, but this idea became overshadowed by the teleological concept and it wasn't until the 19th century that it again came into focus.

> For more than a millenium, western physicians were all disciples of Hippocrates, Aristotle, and Galen. They read about the restorative powers of nature along with all the other phenomena mentioned by these classical authors, but no one, so far as I can discover, commented creatively upon this particular doctrine. If the doctrine meant anything, it was accepted as merely another paragraph to be memorized.[76]

During the time that Greek biology and medicine were the dominant theories, there was in use the term 'physiology' (Gk. 'physiologia'). This term however did not have its modern meaning, but rather it had the much broader meaning of the study of 'physis,' i.e., nature. All of nature, of course, was viewed teleologically by the Greeks.

The overthrow of the authority of medieval writings and the development of the empirical method around the 16th century in Europe had repercussions on biology and medicine. The topics discussed by Hippocrates, Aristotle, and Galen were re-investigated by men who wanted to see for themselves if and where these ancient authors were incorrect. A gradual movement away from the dependence upon the ancient authorities was in progress. In the next few pages we would like to

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[76]Adolph, "Early Concepts," <u>op. cit</u>., p. 742.

discuss the changes in the concept of function which occurred in the 17th to the 19th centuries as well as the resulting shift in the conceptual framework of physiology. What we would like to show is that there were two currents of development in physiology in this period ranging over the 17th to the 19th centuries. One current was a continuation and enlargement of the teleological-anatomical approach of the ancients; the other was the development of a chemical approach which led eventually to 20th century molecular biology. These two currents were developing simultaneously during this period.

First was the development along the lines of classical physiology. The basic elements of anatomy, anatomical parts, were investigated and described with more and more accuracy. Then gradually the function_3 of these anatomical parts were either inferred, or observed. The 'function_3 of x' refers here to the activities of x which are useful or necessary to the organism. Often the activity of a part was observed and then its usefulness inferred. Note then that this development of physiology involved no conceptual changes from the ancient Greeks; the development was in methods of investigation. Classical physiology of the 17th to the 19th centuries was simply carrying out the program determined by the paradigm of ancient Greek biology and medicine. Gradually, too, the concept of holism or organism, i.e., that all the parts of the organism have as their function_3 the unity of the whole organism, became more evident.

The word 'physiology' ('physiologia') was first used in a more modern meaning by Jean Fernel in 1553.[77] He used it to denote the body of knowledge on life processes. He used it to denote normal processes, as opposed to 'pathology' ('pathologia'), and to denote normal processes, i.e., activities in living animals or their parts, as distinguished from anatomy, which studied the lifeless structures of the parts of the organism.

In 1601, Casserius indicated the basic divisions of the study of organisms. "Casserius divides his work into three parts: (1) structure; (2) action--how the parts function; (3) uses--what that function is."[78]

Albrecht von Haller (1707-1777) "has been regarded both by his own age and by posterity as the foremost anatomist and physiologist of his century and as the founder of modern experimental physiology, ..."[79] It was Haller who emphasized the importance of empirical techniques, e.g., in determining which parts of the body have the property of irritability. It was also Haller who firmly linked physiology to anatomy; he defined 'physiology' as 'anatomia animata,' i.e., animated anatomy. For Haller every organ has a specific kind of activity; some of these activities are holistic, i.e., for the good of the whole organism. The muscles for example have their own functions,

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[77]E. J. Field and R. J. Harrison, Anatomical Terms: Their Origin and Derivation (Cambridge, Mass.: W. Heffer & Sons, 1947), p. 61.

[78]F. J. Cole, A History of Comparative Anatomy (London: MacMillan, 1949), p. 114.

[79]Erik Nordenskiold, The History of Biology (New York: Tudor, 1928), p. 238.

i.e., special activities such as walking, standing, flexing, extension, and deglutition, etc. "But the muscles have likewise some common or public actions, by which they are of use to the whole animal."[80] An example of the common action of muscles is seen in their role in the return of the venous blood. Thus physiology under Haller's development studied the activities and purposes of anatomical parts. Physiology at the end of the 18th century "was still mostly a functional commentary to anatomy. . . ."[81]

Johannes P. Müller (1801-1858) was perhaps the most typical and influential physiologist of classical physiology in the 19th century. ". . . His physiological works were actually based very largely on comparative anatomical observations."[82] His Handbuch der Physiologie des Menschen became "the authoritative source of the contemporary conception of life-phenomena."[83] It was with Müller that the teleological concept of function received its strongest support. Müller had been heavily influenced by the German "Naturphilosophie," a school of thought which combined idealism, mysticism, and romanticism and attempted to use this as a conceptual framework to explain living phenomena. Thus Müller, although providing many original and accurate observations, also provided a justification for the theory of vitalism, according to which

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[80]Albrecht von Haller, First Lines of Physiology, XII (1764), 417, p. 242.

[81]Vladislav Kruta, J. E. Purkyne (1787-1869) Physiologist (Prague: Academia, 1969), p. 16.

[82]Nordenskiold, op. cit., p. 386.

[83]Ibid., p. 384.

all the parts of the organism which developed from the embryo, and their activities, worked together for the good of the whole organism because of a uniquely biological, non-physical force in each organism.

In the 20th century and especially the latter half of the 20th century, we find vitalism and teleology almost totally rejected by physiologists. The entire classical approach to physiology has been discontinued for the most part. The study of classical physiology is usually limited to beginning students of biology. And just as in physics, where the beginning student studies classical Newtonian physics while researchers work on quantum and relativistic phenomena, so too in physiology the researchers are working on biochemical systems while beginning students study the classical physiology. What caused the demise of classical physiology? There was no sudden break, rather, during the 18th century a new approach to physiological phenomena was developing side-by-side with the classical physiology. This new approach was the biochemical approach and it came to fruition in the 20th century and gradually pushed aside the classical approach. By the beginning of the 20th century the biochemical approach had developed enough momentum to enable it to take over as the controlling paradigm of physiological research. And thus we have a new theoretical foundation for physiology in the 20th century: molecular biology, and with it a new concept of function: teleonomy. Contemporary physiology is no longer essentially and conceptually tied to anatomy; it is now tied to chemistry. It no longer uses the teleological concept of function, function$_3$; it uses function$_1$, the teleonomic concept, i.e., the concept of a self-regulated biochemical process.

Twentieth century physiology was built on the parallel development of two main ideas--biochemistry and self-regulation. And the idea of self-regulation as an empirical concept was dependent upon ideas of biochemistry. The regulation of the pH level of the blood could not have been determined until scientists first had accurate concepts of pH level and of the chemical make-up of the blood. In short, the full development of the idea of self-regulation, the recognition of the prevalence of self-regulation in the living organism, had to wait for the development of the ideas of chemistry. This is why Hippocrates never went any further than he did with his principle of self-regulation: his chemical knowledge was restricted to the "four humors" theory. Walter B. Cannon has stated that "It is remarkable that features so characteristic of living beings as the steady states should have received so little attention."[84] On the contrary, this is not remarkable at all. Earlier physiologists were not looking at "states" at all. Their attention was directed to anatomical parts; they had no way of studying the chemical states of the body; and thus they had no way of seeing these states as steady.

Hippocrates, as we showed earlier, had a vague concept of self-regulation in his concept of the healing power of nature. This concept was soon overshadowed by the teleology of Aristotle and Galen and was never developed further. It survived only as related to behavior of organisms, under the concept of self-preservation. Biologists noted

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[84] Walter B. Cannon, "Organization for Physiological Homeostasis," Physiological Review, IX (1929), 426.

that when an animal was poked, it responded in defensive behavior. The activities of the animal and its parts were to maintain that animal. The deeper meaning of "maintenance" however, was not developed.

The general trend of the development leading to contemporary physiology occurred roughly in four phases. First, the basic chemical elements were discovered and characterized. Secondly, the investigation of the biochemical processes occurring in living beings was undertaken. This second phase didn't begin to reach any maturity until well into the 19th century. Thirdly, the fixity of biochemical states, i.e., the fact of their stability in the midst of a fluctuating external environment, was investigated. It was the French physiologist Claude Bernard who explicitly brought out this fact. Fourthly, the idea of the negative-feedback circuit as the mechanism used in self-regulated processes was developed. This last idea was explicitly discovered only in the 20th century, although it was vaguely alluded to in the 19th.

Lavoisier, most famous for his development of the concept of oxygen in 1775, saw the relevance of this to respiration in living phenomena. Lavoisier thus spoke of the regulation, i.e., governed exchanges, of substances in living organisms. He further stated that "By varying the means by which effects are compensated, nature arrives at that state of equilibrium and regularity which constitutes health."[85] In 1800 the famous French biologist Bichat defined 'life' as "the sum

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[85]See Adolph, "Early Concepts," op. cit., pp. 747-48.

of those processes [l'ensemble des fonctions"] that resist death."[86] What Bichat had in mind was that the various functions were self-maintaining, i.e., self-regulated and resisted death or dissolution. Bichat was also emphasizing however the holism he saw in organisms, i.e., it is because all the functions work together for the good of the organism that it remains alive.

Herbert Spencer (1820-1903), the noted English philosopher of science, was one of the few who mentioned the idea of function_1 in the 19th century. He acknowledged that the principle of Hippocrates could be stated as follows:

> Among the involved rhythmical changes constituting organic life, any disturbing force that works an excess of change in some direction is gradually diminished and finally neutralized by antagonistic forces, which thereupon work a compensating change in the opposite direction, and so, after more or less oscillation, restore the medium condition. And this process it is which constitutes what physicians call the *vis medicatrix naturae*. . . . This is a conclusion which we may safely draw without knowing the special rearrangements that effect the equilibration.[87]

What Spencer has described in qualitative terms is the concept of a self-regulating system. Note that Spencer believes that the pattern of self-regulation can be recognized, even if we do not know what physical mechanism is involved. Spencer also applied his idea of self-regulation to the evolutionary scale. When he says that "Life is a continuous adjustment of internal conditions to external conditions,"[88]

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[86]See *Ibid*., p. 746.

[87]Herbert Spencer, *First Principles* (New York: D. Appleton, 1896), p. 500.

[88]See Nordenskiold, *op. cit*., p. 495.

he is referring to the adaptation of a species to a new ecological niche. Spencer also made the remark that "the principle of the tendency to stability coincides with the teleological principle."[89] By this he meant that stability in the organism serves some purpose. This shows quite clearly that stability (function$_1$, teleonomy) and purpose (function$_3$, teleology), while two distinct concepts, are not incompatible. Unfortunately, Spencer was limited in his concept of function$_1$ since he still used anatomy as its basis.

> But functions are the correlatives of organs; amounts of functions are, other things equal, the correlatives of sizes of organs; and combinations of functions the correlatives of connections of organs. Hence the structural complexity accompanying functional equilibration, is definable as one in which there are as many specialized parts as are capable, separately and jointly, of counteracting the separate and joint forces amid which the organism exists.[90]

In this quotation Spencer is trying to articulate a quantitative concept of function; probably the earliest known case of this. Unfortunately by being tied to anatomical concepts, he ends up by defining "amounts of function" in terms of the size, number, and combination of organs. With the advance of biochemistry, and 'function' being viewed in a framework of biochemical processes, plus the introduction of concepts of information theory, the goal of Spencer to articulate a quantitative concept of function will have been achieved. It is the ultimate goal of this dissertation to provide just such a concept.

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[89]See Adolph, "Early Concepts," <u>op. cit</u>., p. 760.

[90]Spencer, <u>op. cit</u>., pp. 501-502.

We come now to the last main figure in the development of contemporary physiology of the 17th to 19th centuries--Claude Bernard. Bernard (1813-1878) is usually credited as the pioneer of contemporary biochemical physiology and credited also with originating the idea of self-regulation in the organism. Like most heroes, he has been somewhat over-rated. We hope to provide in the following pages a more accurate view of Bernard's place in the history of physiology and in the history of the development of the concept of function. In particular he will be seen as a link between classical and contemporary physiology. He was contemporary in his insistence both upon the use of chemical techniques and upon the stability of the internal states in mammals. He was classical in his claim that physiology must use the concepts of anatomy and in his emphasis on physiology as directed toward improving medicine. Also Bernard had only a qualitative concept of self-regulation, and he was in a qualified way opposed to statistical and other mathematical techniques in physiology, and he had no idea of the actual mechanism of self-regulation. Also, since Bernard's time, patterns of self regulation have been found in other classes than mammals, i.e., self-regulation is not restricted to the "higher animals."

The claim is made by L. L. Langley in his book Homeostasis that what led Claude Bernard to the concept of self-regulation was his numerous observations on the fixity or stability of the milieu interieur, i.e., the blood and lymph systems, in some mammals. According to Bernard himself, however, these observations led him to two other conclusions. His first conclusion was that the fixity of the milieu interieur was a condition for free and independent life, i.e., the life of the organism as independent of the vagaries of its environment. Secondly, and this was the most important idea for Bernard, it proved that living processes were deterministic and obeyed physico-chemical laws; this refuted vitalist physiologists who maintained that physico-chemical laws did not hold in the living organisms.

The central conceptual problem that occupied Bernard in all his writings was a methodological one. Bernard wanted to see physiology (and medicine) put on an experimental basis. Bernard was reacting against the German "Naturphilosophie" and against the accompanying doctrine of vitalism, both of which, in his view, were hindering the progress of scientific physiology. The vitalist argument went something like this. A living process is deterministic if and only if it changes in proportion to the forces acting upon it. Thus if you apply more and more heat to a metal the metal becomes hotter and hotter; or the more you apply heat, the more the metal expands. Now in living phenomena the processes do not change in proportion to the external forces acting upon them. If you inflict injury upon a tissue the tissue grows back, if you increase the external temperature around a man, his body temperature remains the same. Thus living processes are not deterministic, mainly because they do not change and reach new equilibrium points as chemical and physical forces do.

Bernard recognized that on the level of the whole organism there does seem to be a violation of the deterministic character of physico-chemical laws and if we define living processes in terms of the whole organism, then determinism does not seem to hold there. Bernard, then, defined living processes as processes going on inside the organism; they are properties of what he called "histological units," i.e., clumps of tissue. These histological units which are the actual sources of the manifestations of life are deterministic, i.e., if their environment changes they change accordingly. However, their environment, the "milieu interieur," never changes! The milieu interieur acts as a buffer, or protecting agent between the external environment, which Bernard called the "cosmic environment," and these histological units of life. Thus life processes are deterministic, they will change with their environment, but their environment never changes so thus the stability. Thus the stability is not in the life processes themselves but in the milieu interieur, i.e., the blood and lymph.

The consequence for physiologists is important. To describe living processes we must compare their behavior vis-a-vis the milieu interieur, not the cosmic environment. "We must, moreover, learn that the intimate particles of an organism exhibit their vital activity only through a necessary physico-chemical relation with immediate environments which we must also study and know."[91] The input of the liver is from the bloodstream and not from what we ingest through our mouth. The physiologist must study the internal states of the organism; he

[91]Claude Bernard, An Introduction to the Study of Experimental Medicine, trans. by H. C. Greene (New York: Dover, 1957), p. 63.

must study the blood and lymph system and other tissues and cells which are in this environment. To find out how the liver operates we must vary the amount of sugar or fat in the blood, not in the diet, since changes in the diet never get through to the liver, they are compensated for, equalized by the regulatory aspect of the blood.

> Considered in the general cosmic environment, the functions of man and of the higher animals seem to us, indeed, free and independent of the physico-chemical conditions of the environment, because its actual stimuli are found in an inner, organic, liquid environment. What we see from the outside is merely the result of physico-chemical stimuli from the inner environment; that is where physiologists must build up the real determinism of vital functions.[92]

The above quote shows that for Bernard self-regulation was restricted to a small part of the living phenomena, namely, the milieu interieur. "Vital functions" were for him still unregulated. The blood and lymph systems are regulated but other "functions" are not. In the 20th century, as we will show in a later section, it was discovered that other functions were regulated too; in fact, all functions in the body are regulated. Bernard's concept of self-regulation was restricted also in the organisms to which he applied it. "In fine, then, only the warm-blooded animals and man seem to escape cosmic influences and to have free and independent manifestations."[93] Research in the 20th century has shown that regulation in some form pervades all classes of organisms.

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[92]Ibid., p. 79.

[93]Ibid., p. 97.

In summary, then, Bernard claimed that if one accepted the existence of a stable milieu interieur and accepted that the histological units imbedded in this milieu interieur were the sources of the phenomena of life, then a strict physico-chemical determinism of life processes was compatible with the overall independence of the organism from the effects of its external physico-chemical environment. In other words, Bernard's conclusion was that the living processes are not regulated; only the milieu interieur is regulated.

What should be emphasized is that developing the idea of regulation was subordinate to showing the physico-chemical determinism of the living units. One could reply to Bernard that he has shown that the living units in the milieu interieur are deterministic; but what about the milieu interieur itself? What makes it such a protector? Could it not be considered as violating physico-chemical determinism? In other words, Bernard removed the need for a vitalistic explanation in the histological units of the body, but he did not remove the possibility for a vitalistic explanation of that marvelous regulatory aspect of the blood and lymph. Actually it wasn't until well into the 20th century, with the development of the idea of negative feedback circuits and their embodiment in a large number of machines that the deterministic character of regulatory activity was given a satisfactory explanation.

Physiology, for Bernard, investigated the internal states of the organism, the physico-chemical manifestations of living units. Chemistry then was a necessary tool for physiology. In this Bernard clearly belonged to the contemporary school of physiology. This did not mean however, that anatomy was to be relinquished. For Bernard, anatomy was also a necessary tool for physiology. To this extent he belongs to classical physiology. But although chemistry and anatomy were essential tools, physiology was not reduced to either. "In a word, biology has its own problem and its definite point of view; it borrows from other sciences only their help and their methods, not their theories."[94]

What then is the "physiological" point of view? And to what extent do anatomy and chemistry enter into it? Regarding the basic units that physiologists deal with, Bernard states that they are anatomical or histological, rather than chemical. "For physiologists, the truly active elements are what we cann anatomical or histological units . . . physiologically considered, they are as simplified as possible in that their vital properties are the simplest that we know; vital properties which vanish when we happen to destroy this elementary organized part."[95] The techniques of investigation of the physiologist then are designed to enable him to reduce complex living phenomena down to these histological units.

> By following the same analytic path, physiologists should succeed in reducing all the vital manifestations of a complex organism to the play of certain organs, and the action of these organs to the properties of well-defined tissues or organic units. Anatomico-physiological experimental analysis, which dates from Galen, has just this meaning, and histology, in pursuing the same problem today, is naturally coming closer to the goal.[96]

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[94]Ibid., p. 95.

[95]Ibid., p. 73.

[96]Ibid.

Bernard is thus not maintaining that physiology is reducible to chemistry (or anatomy). "Though we can succeed in separating living tissues into chemical elements or bodies, still these elementary chemical bodies are not elements for physiologists."[97] This is mainly due to the fact that at the time of Bernard, no connection between chemical properties and vital phenomena were known. "In the present state of the science, it would be impossible to establish any relation between the vital properties of bodies and their chemcial composition; because tissues and organs endowed with the most diverse properties are at times indistinguishable from the point of view of their elementary chemical composition."[98] In the more than 100 years that have passed since Bernard made these remarks, much has been learned about these relationships. Thus although Bernard actively used biochemical techniques of invertigation, he did not make the universal claim that <u>all</u> living processes, functions$_1$, were solely of a biochemical nature.

Physiology then, although using chemistry and anatomy, has a conceptual foundation different from them. Bernard never clearly brings out what this is. He defines 'physiology' in one place as "the science whose object it is to study the phenomena of living beings and to <u>determine</u> the material conditions in which they appear."[99] In another place he defines 'physiology' as divided into three parts: general physiology, descriptive physiology, and comparative physiology. General physiology

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[97] <u>Ibid</u>.

[98] <u>Ibid</u>.

[99] <u>Ibid</u>., p. 66.

studies "fixed, invariable elementary properties, which are the fundamental basis of all the manifestations of life."[100] What the term 'properties' means is stated clearly by Bernard. A property is a simple irreducible biological fact; it cannot be explained by anything else. The contractility of protoplasm is a property. Properties belong to the cell or to protoplasm. This is the special viewpoint of physiology. General physiology studies the uniquely living properties in the organism. Bernard defines descriptive and comparative physiology thusly: "Descriptive physiology gives us, on the contrary, knowledge of the form and the special mechanisms that life uses to manifest itself in a determined living being. . . . If now one wants to compare the forms and diverse mechanisms, varying infinitely in living beings, in order to deduce the laws of these phenomena, this is the work of comparative physiology."[101] Descriptive and comparative physiology study functions_1 according to this definition.

Bernard does give a clear definition of 'function' as he viewed its use in physiology. In the higher organisms, each cell specializes into a certain kind of activity, necessitating that the specialized cells be unified into some overall organization. A function is such an organization of cellular activities. Thus the activities of a multitude of anatomical elements are used in the function. ". . . But the function is not the brute sum of elementary activities of juxtaposed

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[100]Claude Bernard, Lecons sur les Phenomenes de la Vie Communs aux Animaux et aux Vegetaux (Paris: Librairie Philosophique J. Vrin, 1966), p. 372 (all translations from this work are mine).

[101]*Ibid*., p. 375.

cells; these component activities are made to endure one by the other; they are harmonized and organized in such a way as to work together to a common result. It is the result glimpsed by the mind which forms the connection and the unity of these component phenomena, which makes the function."[102] Thus, a 'function' is a grouping of cellular reactions, properties, or activities. What identifies a function is the common, determined result of the activity.

Bernard insists that while there is a conceptualization involved in speaking of functions, nevertheless functions do rest on well-determined material facts. "It is the mind which grasps the functional relation of the elementary activities; which ascribes a plan, a goal to the things which it sees occurring, which perceives the fulfillment of a result of which it has conceived the necessity. Now the agreement can only be complete on the well-determined material fact, never in the idea. From there arises the discord and disagreement of the physiologists in the classification of functions."[103] Bernard is here making a positivistic point that only the elementary phenomena, i.e., properties, are objective facts, the functions are subjective, although based on objective facts.

It becomes clear then that 'circulation,' for example, is predicated of the entire organization of cellular activities; it cannot be predicated of any individual part, e.g., a cell. "There is a respiratory function, a circulatory function, but there is not in the

[102] Ibid., p. 370.

[103] Ibid., p. 371.

contractile elements which make it up a circulatory property. There is a vocal function in the larynx, but there are not any vocal properties in its muscles, etc."[104] Thus functions are ascribed only to systems of cellular activities. Bernard says that "Actions and functions, on the contrary, only belong to organs and to physical mechanisms, that is, to ensembles of anatomic parts."[105] Properties, on the other hand, belong to the cell, to the protoplasm.

Note that the 'function' is _not_ the result but is the entire process including the result. 'Function' as analyzed by Bernard is not the goal or purpose of the process, it is the entire process. He lists three functions which all scientists admit, viz., circulation, digestion, and respiration. He adds that there are other patterns of cellular activities on which there is not general agreement as to whether they should be called 'functions' or not.

Put in another way, then, general physiology studies properties, and descriptive and comparative physiology study functions. This means for Bernard that physiological properties as studied in general physiology, are generalizable to all organisms, whereas the functions are not generalizable, they must be empirically ascertained for each new type of organism. Bernard uses the example of facial nerves in a horse and man. Though the cellular properties are the same in both, they do not perform the same functions. If they are cut in the horse, the horse dies due to asphyxiation; if they are cut in a man only paralysis of the

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[104] _Ibid_., pp. 371-72.

[105] _Ibid_., p. 370.

face occurs. Thus facial nerves in the horse are part of the organization for regulation of respiration; in man they are part of the organization for muscular movement.

Thus for Bernard the concept of function means an organized interplay of elementary living activities. The idea of self-regulation is not part of the meaning of 'function.' In all of the examples given of physiological investigations in the Introduction to the Study of Experimental Medicine, none brought up the concept of self-regulation. In his Lecons, he did use an example which showed regulation of the water content of the milieu interieur of the body but this example also showed the organized interplay of various activities (in achieving this regulation). Thus for Bernard 'function' involved the concepts of teleology or holism. "One can, as a physiologist-philosopher, admit in this arrangement of ideas a type of particular finality, an intra-organic teleology: the grouping of vital phenomena into functions is the expression of this thinking."[106] Bernard thus had a view of function which was contemporary in emphasizing how something functioned, and classical in emphasizing for what purpose it functioned. "It [vivisection] is always a question of separating or altering certain parts of the living machine, so as to study them and thus to decide how they function and for what."[107]

In summary then, Bernard was a classical physiologist in his use of anatomy and of teleology. He was contemporary in his emphasis

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[106]Ibid., p. 340.

[107]Bernard, Introduction, op. cit., p. 104.

on using physico-chemical techniques and in his emphasis of the idea of self-regulation. His proficiency with these techniques and the results he obtained were limited by the immature state of biochemistry and biophysics at that time. Bernard was also contemporary in that he freed the concept of function from reliance solely upon anatomical concepts; instead he made it rely upon metabolic and physico-chemical concepts, in addition to anatomical ones. The concept of self-regulation was not, however, as deeply entwined in his thinking as it is for today's physiologists.

Nevertheless, Bernard did recognize the concept of self-regulation. And although he was not clear on the mechanisms involved, and although he limited the scope of the idea, he did express the idea. What are the details of Bernard's concept of self-regulation? And what is its relationship to his concept of function? Bernard viewed the living organism physiologically as a machine.

> The organism is merely a living machine so constructed that, on the one hand, the outer environment is in free communication with the inner organic environment, and, on the other hand, the organic units have protective functions, to place in reserve the materials of life and uninterruptedly to maintain the humidity, warmth and other conditions essential to vital activity.[108]

Now he also has spoken of life as creative. "As long as a living being persists, it remains under the influence of this same creative vital force, and death comes when it can no longer express itself."[109] Here, however, Bernard is talking about ontogeny, the

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[108] Ibid., p. 76.

[109] Ibid., p. 93.

creative development of the individual from a germ cell or embryo to a mature organism. This organization of the individual according to some plan results from a vital force, but this occurs over the life of the individual. The physiological aspect, the stability of the organism's functions is physico-chemical. Also, Bernard saw the use of an information processing or communication system in this regulation. He said, ". . . we then understand how a completely chemical function can be regulated by a nervous system, so as to supply organic fluids in conditions that are always the same."[110] Bernard, like Herbert Spencer, alludes to a quantitative concept of "vital phenomena," although giving no details except that it would develop in the context of machine models of physico-chemical systems. "Physiologists, indeed, have only to take apart the living machine, and with the help of tools and processes borrowed from physics and chemistry, to study and measure the various vital phenomena whose law they seek to discover."[111] Bernard mentions two specific machine models of living organisms, both of which illustrate a stable milieu interieur and which do not explicitly mention the idea of negative feedback or automatic control; they use the idea of passive regulation such as is found in a thermos bottle (dewar flask), i.e., external changes cannot pass through into the interior. Regarding the first model Bernard says, "But warm-blooded animals keep their organic units, as it were in a hothouse."[112] In the

[110] Ibid., p. 90.

[111] Ibid., p. 94.

[112] Ibid., p. 119.

19th century, hothouses were insulated from the weather but had no self-regulated heating system. The other model is described thusly:

> Moreover, we easily understand what we see here in the living machine, since the same thing is true of the inanimate machines created by man. Thus, climatic changes have no influence at all on the action of a steam engine, though everyone knows that exact conditions of temperature, pressure and humidity inside the machine govern all its movements.[113]

Thus for Bernard the automatic control aspect was not part of the idea of self-regulation. One example that Bernard uses, however, seems to prefigure the idea of control for regulation and Bernard speaks of what he calls "mechanismes compensateurs."

> The mechanisms which make the quantity of water vary and restore it are quite numerous; they set in motion a multitude of apparatuses of secretion, exhaling, ingestion and circulation, which transport the ingested and absorbed liquid. These mechanisms vary but the result in which they co-operate is constant: the presence of water in a precisely determined amount of the milieu interieur, the condition of the free life.[114]

Bernard's concept of the self-regulated functions in the living organism, whose investigation is the problem of physiology, can thus be described as complete but immature. Immature in that (1) the science of biochemistry was not developed as it is today. Thus for Bernard the biochemical mechanisms of many vital processes were not known and he thus referred to them as properties irreducibly vital, although having physico-chemical conditions; (2) Bernard saw self-regulation in only a few groups of animals and only in a few of the animals' processes, mainly warm-blooded animals and their blood; (3) Bernard

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[113] Ibid., p. 98.

[114] Bernard, Lecons, op. cit., p. 116.

had no concept of the internal regulatory mechanism itself. His concept of self-regulated functions was complete, since it had the following characteristics: (1) the physiological processes must refer to the input as well as the output of the functional system for their description. ". . . Life results from contact of the organism with its environment; we can no more understand it through the organism alone than through the environment alone."[115] Thus the self-regulated physiological processes are as much input-directed as goal, i.e., output-directed. The concept of self-regulation always assumes regulation with respect to some disturbance; (2) the concept of self-regulation is most succinctly expressed in this way: "We see the higher organisms uniformly exhibit their vital phenomena, in spite of variations in the surrounding cosmic environment. . . ."[116] In more contemporary terms, Bernard is saying that the amount of output variety is small compared to the amount of input variety. (3) Bernard was aware that vital functions were basically physico-chemical processes, and that these processes are coordinated in a special arrangement. He said, "Admitting that vital phenomena rest upon physico-chemical activities, which is the truth, the essence of the problem is not thereby cleared up."[117] In other words, knowing the biochemical is only part of the physiological description, the rest of the description must show the patterns of behavior of these processes. And the most general pattern is the self-regulation pattern.

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[115]Bernard, Introduction, op. cit., p. 75.

[116]Ibid., p. 75.

[117]Ibid., p. 50.

20th Century

In this section of this chapter we will show how the concept suggested in the earlier centuries, self-regulated physiological process, is brought to fruition in 20th century physiology. We intend to show that the highest development occurred only after the Second World War. Thus the formal quantitative basis of physiology is only 25 years old; and so the concept of function as described here is in the vanguard of physiological thought.

Modern dictionaries of biology and medicine, in their definitions of 'function,' contain references to the concept of a regulated process. In A Dictionary of Biology, 'function' is defined thusly: "The function of part of an organism is the way in which that part helps maintain the organism to which it belongs alive and able to reproduce; or sometimes it means simply the way it works, the processes going on in it."[118] In Stedman's Practical Medical Dictionary we find 'function' defined as "The special action or physiological property of an organ or other part of the body."[119] The Collegiate Dictionary of Zoology defines 'function' as the "Characteristic role or action of any structure or process in the maintenance of normal metabolism and behavior of an animal."[120] Now how can we explicate, i.e., precisely express,

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[118]M. Abercrombie, C. J. Hickman and M. L. Johnson, A Dictionary of Biology (Chicago: Aldine Publishing Co., 1962), p. 94.

[119]Stanley T. Garber, Stedman's Practical Medical Dictionary (Baltimore: Williams & Wilkins Co., 1942), p. 425.

[120]Robert W. Pennak, Collegiate Dictionary of Zoology (New York: Ronald Press Co., 1964), p. 205.

this "special action," which "maintains the metabolism"? Although the definitions imply that each function is different they also imply that there is something similar about them all, by which they are all known as 'functions.' This common element among all functions is the manner in which they maintain life in the organism, i.e., by self-regulated processes.

Walter B. Cannon is probably the most well-known physiologist of the 20th century, and the one who more than any other 20th century scientist was responsible for developing the motion of a self-regulated process. By examining Cannon's work we can gain a clear insight into the concept of $function_1$ as it is used in the 20th century. Cannon sometimes used the concept of $function_3$, for pedagogical or heuristic purposes, and this can be seen in his writings.

As we have seen, Claude Bernard referred to the concept of self-regulation in the 19th century. In the 20th century, Walter Cannon also referred to this concept. It seems that Cannon and Bernard developed these concepts independently of each other. Bernard, by studying the internal biochemical processes, was struck by the stability of these processes. Cannon, working on the autonomic nervous system, began to see that this system was controlling the regulation of the processes of the body. Cannon also worked with Arturo Rosenblueth on a book entitled Autonomic Neuro-Effector Systems, published in 1937. Then in 1943 Rosenblueth, Norbert Wiener, and J. Bigelow published an article in Philosophy of Science entitled "Behavior, Purpose, and Teleology," in which one form of regulation, that found in servomechanisms, was used as a model for biological phenomena. (The authors were using the correct explicatum; however they were applying it to function$_3$ instead of function$_1$.) Wiener published his famous book Cybernetics in 1948. Thus what we might call the "cybernetic tradition" in physiology goes back, as we just showed, to the work of Walter Cannon. This progress was described by E. F. Adolph in 1961 in the following way: "A century ago concepts of physiological regulation rarely entered the thoughts of physiologists. Now they constitute a cornerstone in biological science as a whole."[121] Cannon himself phrased it this way: "Indeed, regulation in the organism is the central problem of physiology."[122]

That Cannon's views on the stability of life processes are the same as Bernard's can be seen by the following quote.

> The highly developed living being is an open system having many relations to its surroundings--in the respiratory and alimentary tracts and through surface receptors, neuromuscular organs and bony levers. Changes in the surroundings excite reactions in this system, or affect it directly, so that internal disturbances of the system are produced. Such disturbances are normally kept within narrow limits, because automatic adjustments within the system are brought into action, and thereby wide oscillations are prevented and the internal conditions are held fairly constant.[123]

While Bernard used this phenomena of internal stability to show that warm-blooded animals possess the free life and to show that vital processes are deterministic, Cannon began to investigate this

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[121]Adolph, "Early Concepts," op. cit., p. 738.

[122]Cannon, "Organization," op. cit., p. 427.

[123]Ibid., p. 400.

phenomena of stability, to seek the description of and mechanism for it. He coined the term 'homeostasis' to express this concept.

> The present discussion is concerned with the physiological rather than the physical arrangements for attaining constancy. The coordinated physiological reactions which maintain most of the steady states in the body are so complex, and are so peculiar to the living organism, that it has been suggested (Cannon, 1926) that a specific designation for these states be employed--homeostasis.[124]

According to Cannon, he used 'homeo' ('similar') rather than 'homo' ('identical') to show that although there was stability and constancy, it was not perfect constancy, i.e., there are slight fluctuations in the internal environment. He used 'stasis' to refer to 'states' resulting from an interplay of forces. "As in the branch of mechanics called "statics," the central concept is that of a steady state produced by the action of forces; homeostatics might therefore be preferable to homeostasis."[125] Cannon goes on to say that he chose 'stasis' rather than 'statics' to emphasize that this is a physiological and not a physical concept. Thus the concept of homeostasis involves the idea of a stable state produced by an interplay of forces. This concept is not different from Bernard's concept of the fixity of the milieu interieur.

Some authors have read much more into Cannon's original concept than Cannon intended. The actual mechanisms of homeostasis, the negative feedback concept, was developed after Cannon. L. L. Langley, for example, claims that 'stasis' in 'homeostasis' is derived from the

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[124] *Ibid.*, p. 401.

[125] *Ibid.*

medical term 'stasis,' i.e., a blockage, such as occurs in a blood vessel. He concludes "Homeostasis, then, conveys, the impression of a mechanism that prevents or blocks change, that keeps things the same."[126] According to Langley, Cannon's concept goes beyond Bernard's to suggest "the concept now referred to as negative feedback, that is, if there is a deviation in one direction, there is a reaction in the opposite direction."[127]

First of all, 'homeostasis' according to Cannon's own words, referred to a stable state, a fixed internal milieu. This stable state was achieved by the arrangement of negative feedback, but, this idea of negative feedback is an addition to the concept of homeostasis.

There are two ways of looking at steady states, two patterns of regulation: passive regulation and active regulation. A thermos bottle (dewar flask) is an example of passive regulation. External changes in the environment are resisted by some form of insulation. Now Bernard used examples of this type when he suggested a steam engine as operating normally in spite of environmental changes in temperature, humidity, and pressure. The steam engine shows passive regulation, i.e., because of the thickness of the metal composing it, it is insulated from external environment, and changes in the external environment do not affect the operation of the steam engine (within limits, of course).

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[126]L. L. Langley, Homeostasis (New York: Reinhold Publishing Corp., 1965), p. 9.

[127]Ibid.

Active regulation is regulatory action, homeostasis, achieved through a compensatory mechanism, in which (1) external changes are sensed internally, (2) an equivalent amount of compensation to the internal state is applied, resulting in (3) the internal state is returned to its original value.

Thus one can have a stable internal milieu without active regulation. In living organisms it is primarily regulation of the active type that is found. Self-regulation, i.e., the maintenance of "steady state" conditions of life, has been recognized for centuries, as I have earlier taken pains to show. Yet without a concept of active regulation, i.e., of a compensatory system such as negative feedback, physiologists and biologists postulated various agents, especially a vital agent, vital force or entelechy to account for the maintenance of these steady states. It was only with the advent of the mature concept of negative feedback that physiology could finally replace the vital force with a quantitative mechanistic model.

Cannon listed the basic elements involved in the concept of homeostasis. In his 1929 article he listed postulates regarding homeostatic regulation. The first was this: "In an open system such as our bodies represent, compounded of unstable material and subjected continually to disturbing conditions, constancy is in itself evidence that agencies are acting, or ready to act, to maintain this constancy."[128]

This summarizes the concept of regulation as used by Bernard and Cannon. The elements of this concept are:

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[128]Cannon, "Organization," op. cit., p. 424.

1. There is an open channel for transfer of information, energy, substances between our bodies and the external environment;
2. The external environment is not stable, it consists of a variety of changes;
3. On the basis of (1) and (2) one would expect the environmental changes to be carried into the internal states of the body and these internal body states to change accordingly;
4. But, there is in fact a constancy of these internal states;
5. Therefore on the basis of (1), (2), and (4) some agency must be acting to maintain this constancy.

So far then Cannon has established the same thing that Bernard established in the 19th century. Note that (5) above is very vague and could be used to support the existence of a vital force; in fact, (5) is simply a restatement of (4).

Cannon now advances to his second postulate: "If a state remains steady it does so because any tendency toward change is automatically met by increased effectivenss of the factor or factors which resist the change."[129] Here, of course, Cannon is referring in a qualitative way to what we today call "negative feedback." Note that this postulate is a conditional statement. This is because self-regulatory mechanisms are not indestructible; there are limits beyond which they will be destroyed. Cannon does not want to say that bodily factors are always regulated. At 500° centigrade the human body will not stay regulated.

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[129]Ibid., p. 425.

Thus by using two separate postulates, Cannon indicates that the concept of regulation (first postulate) and self-regulation (second postulate) are distinguishable. In physiological descriptions these two are combined to provide the concept of a self-regulated process.

Cannon also has a postulate about the organizational aspect of regulated systems, i.e., that they may contain more than one means of regulation. "The regulating system which determines a homeostatic state may comprise a number of co-operating factors brought into action at the same time or successively."[130] Thus temperature is kept constant by sweating, change in blood circulation rate, change in muscular activity, etc. This points out a further distinction among self-regulated systems, i.e., some are simple and some are complex. Thus Cannon has presented his concept of homeostatic regulation in physiology. It contains three elements: (1) that of a stable internal environment in the face of external disturbances, (2) that of a compensatory, i.e., active, mechanism, and (3) this mechanism can be simple or complex.

The full development of the concept of self-regulation did not come until after Cannon's work. Cannon himself sometimes discussed his work in terms of the older, classical concept of function$_3$, which he referred to as 'utility.' What we would like to show in the next few pages is how Cannon used function$_3$ as a means to popularise his physiological research. In the 20th century, the concept of function$_3$, the usefulness to the whole organism, or the role played in the whole, is found in physiological literature, but only as a pedagogical tool.

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[130] <u>Ibid</u>., p. 426.

It is used in non-technical, introductory, and popular writing, mainly because of its close empathic relationship with human purpose and goal-directedness. Cannon has written two non-technical works, in both of which we find the concept of function$_3$ used. The Wisdom of the Body, first published in 1932, is one of these books. In this book Cannon claims, "I shall strive to describe the physiological agencies and events in terms which will be clear to anyone who has had a simple training in biology and general science."[131] The other famous work by Cannon is his Bodily Changes in Pain, Hunger, Fear and Rage, published in 1929. This work too is non-technical. Cannon has in this work "tried also to eliminate or incidentally to explain the technical terms, so that the exposition will be easily understood by any intelligent reader even though not trained in the medical sciences."[132] That both of these works are non-technical science was later confirmed by Cannon himself. "I have taken time to express in popular form accounts of various groups of investigations which have been carried on by me and my collaborators. Thus the researches on the effects of emotional excitement were presented in a manner which could be generally understood in Bodily Changes in Pain, Hunger, Fear, and Rage, and the studies concerned with the maintenance of steady states in the organism were described in The Wisdom of the Body."[133] Now it is in these two works

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[131] Walter B. Cannon, The Wisdom of the Body (New York: W. W. Norton & Co., 1939), p. 26.

[132] Walter B. Cannon, Bodily Changes in Pain, Hunger, Fear and Rage (Boston: Charles T. Branford Co., 1953), p. viii.

[133] Cannon, The Way of an Investigator, op. cit., p. 166.

that a concept of function as "utility" or "serving a purpose" is found.

The general thesis which Cannon is setting out in Bodily Changes in Pain, Hunger, Fear and Rage is that "the bodily changes which attend great excitement are directed towards efficiency in physical struggle."[134] This thesis describes what we have called 'purposeful' or 'teleological' behavior. The teleological framework of this book will thus determine the meaning of 'function' as we will see with specific illustrations.

Early in the book Cannon says that "the secretions of the digestive glands and the chemical changes wrought by them are of little worth unless the food is carried onward through the alimentary canal into fresh regions of digestion. This function is performed by peristalsis. . . ."[135] In other words the peristalsis performs the function of carrying food onward through the alimentary canal and this carrying onward of the food is necessary otherwise the chemical processes of digestion would be of little worth.

Now another case occurs, where 'function' is used with regard to the cranial nerves. "A glance at these various functions of the cranial division reveals at once that they serve for bodily conservation."[136] Thus knowing the function of x, one thus knows how x serves for conserving the body.

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[134]Cannon, Bodily Changes, op. cit., p. ix.

[135]Ibid., p. 12.

[136]Ibid., p. 29.

In Chapters III and VII Cannon presents the experimental data of his research. The word 'function' does not occur here, which shows that 'function' in the sense of purpose or utility is more a part of non-technical (as opposed to technical) physiology. Chapters III to VII are of course technical physiology.

Chapter VIII is entitled "The Specific Role of Adrenin in Counteracting the Effects of Fatigue." Cannon says, "Some of the earlier investigators of adrenal function . . . inferred from experiments on the removal of the glands that the role they played in the bodily economy was that of neutralizing, destroying or transforming toxic substances produced in the organism as a result of muscular or nervous work."[137] What Cannon is saying here is that when the adrenals were removed the body was not able to neutralize or destroy toxic substances which the muscles produce when working heavily. From this it was inferred that the adrenal glands' function or role was to neutralize or destroy the toxic substances produced by the muscles. These are what we have called 'ablation experiments'; they serve to verify the function_3 of the item.

In Chapters IX and X Cannon's thesis is that a function of adrenin is to decrease the coagulation time of blood, thereby allowing wounds to heal faster, thereby helping the organism stay alive. He puts it this way: ". . . the faster coagulation which follows emotional excitement is due to adrenal discharge from splanchnic stimulation."[138]

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[137] Ibid., p. 125.

[138] Ibid., p. 174.

Here Cannon is saying that adrenin production causes faster coagulation; he then infers that a function of adrenin production is faster coagulation time.

In Chapter XIII Cannon is most explicit about his theoretical framework; he spells out quite clearly the interpretation of his research. First of all he makes a radical separation between the facts of observation, i.e., the data, and the interpretation or inferences drawn from this data. He summarizes the facts thusly:

> Our inquiry thus far has revealed that the adrenin secreted in times of stress has all the effects in the body that are produced by injected adrenin. It cooperates with sympathetic nerves impulses in calling forth stored carbohydrates from the liver, thus flooding the blood with sugar; it helps in distributing the blood to the heart, lungs, central nervous system and limbs, while taking it away from the inhibited organs of the abdomen; it quickly abolishes the effects of muscular fatigue; and it renders the blood more rapidly coagulable.[139]

Then Cannon gives the interpretation of these facts by showing the "utility" of them. The utility of the increased adrenin output is fourfold: (1) it releases sugar as a source of muscular energy; (2) it is an antidote to the effects of muscle fatigue; (3) it shifts the blood flow from the abdominal viscera to the central nervous system, lungs, heart, and skeletal muscles; and (4) it stimulates the rapid coagulation of the blood.

Having stated the above four functions$_3$ of adrenin, one can further ask, what are the functions$_3$ of each of these functions$_3$, e.g., What is the function$_3$ of releasing sugar? Here we see that Cannon has an hierarchy of functions$_3$.

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[139] Ibid., p. 193.

1. The $function_3$ of the emotions is to stimulate discharge of adrenin.
2. The $function_3$ of adrenin is to cause blood sugar increase.
3. The $function_3$ of blood sugar increase is to provide energy for muscular movements.
4. The $function_3$ of muscular movements is to aid in fighting or in fleeing.
5. The $function_3$ of fighting or fleeing is the survival of the organism.[140]

Cannon has, in this popular exposition, related his concept of $function_3$ to survival. The problems with this have been discussed earlier. Cannon at no time ever did any research specifically on survival or adaptation. He is appealing to the common sense experiences of survival, some of which he gathered in his informal observations of soldiers during World War I.

In summary then of Cannon's work, we can see that he did develop the concept of self-regulation by his introduction of the notion of "steady state." His use of teleology was restricted to the more popular versions of his work.

The next conceptual breakthrough, which influenced the concept of self-regulation, occurred outside the area of physiology. This was the concept of negative feedback which first appeared in a published article in 1934. In that year, H. S. Black of the Bell Telephone Laboratories published a description of a negative feedback amplifier.[141] At first negative feedback was used only in electronic amplifiers. Then during World War II the theory of feedback amplifiers was directly

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[140] Ibid., p. 197.

[141] H. S. Black, "Stabilized Feedback Amplifiers," Bell System Technical Journal, XIII (1934), 1-18.

applied to the design of servomechanisms and automatic control systems. After the war these servomechanisms and the principles of their operation began to be used as models for processes in living organisms. The more research that was done, the more the universality of self-regulation in living organisms of all species could be seen. This was a departure from the views of Bernard and Cannon, who felt that only warm-blooded animals possessed regulation. Thus in 1961, Adolph could say, "Arrangements for self-governments have been found in all vital activities that have been suitably examined. Such intrinsic controls cannot be wholly separated from processes themselves."[142]

Thus the basic theoretical framework of physiology today uses what is called the "cybernetic approach." This approach uses "black-box" models, i.e., systems composed of units distinguished by their transfer functions, i.e., the relation of output to input values. Physiologists "now concentrate on the more precise study of how much control is exerted, and how and when it is activated. Along with the refined analysis of transmission has developed the correlation of input and output in specific systems."[143] With physiological functions now able to be described in formal, quantitative ways, the goal which Herbert Spencer referred to in the 19th century, a measure of the amount of function, is now possible.

If one examines the current literature of physiology, one can arrive at the following list of accepted vital functions$_1$:

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[142]Adolph, "Early Concepts," <u>op. cit</u>., p. 737.

[143]<u>Ibid</u>., p. 751.

1. circulatory system
2. digestive system
3. endocrine system
4. excretory system
5. nervous system
6. reproductive system
7. respiratory system.

It can be seen that these functions are systems, i.e., complex processes. It is also well-known that each of these systems is a self-regulated system, e.g., the respiratory system consists of various biochemical processes coordinated with a negative feedback process to maintain specific levels of oxygen, carbon dioxide, etc.

The traditional relationship of anatomical concepts with these systems has led to much confusion. This arrangement of the above seven systems has its origin in the days when physiology was still tied to anatomy. Thus the circulatory system was tied to the heart and blood vessels. Often when one speaks of "the circulatory system" this brings to mind the heart and blood vessels, i.e., the anatomical system. In one sense, a psychological one, this is understandable, since the human mind seems to depend upon concrete objects for images rather than abstract descriptions of processes.

However from a methodological standpoint this arrangement of the vital functions is very inadequate and as research in physiology progresses, the inadequacy becomes more apparent. In general we can say that each of these functions is interdependent upon the other.

Thus the digestive system, i.e., the process of food intake; digestion, and absorption, involves also the circulatory system, e.g., in absorption; the endocrine system, e.g., in digestion; the excretory system, e.g., in fluid volume control; the nervous system, e.g., in food intake; the reproductive system, e.g., in production of yolk-sac; and the respiratory systems, e.g., in providing oxygen used for oxidation of food products. In fact, then, in anatomical systems there is more than one function going on, e.g., in the blood vessels both circulatory, digestive, excretory, endocrine and nervous processes are in action.

Thus with the realization of the inadequacies of anatomical relationships for physiological investigations, physiologists have turned to the concept of a system, i.e., a process, a pattern of behavior, of biochemical and biophysical elements. This is the approach now called the cybernetic approach. This has freed physiology from a direct reliance upon anatomy and has led to the new emphasis upon self-regulation. Thus what was previously described as 'kidney function,' then as 'the excretory system,' can now be described as fluid-volume and ionic regulation systems. The kidney as an anatomical unit is viewed merely as the localization of the function, i.e., the place where the major activity occurs. Some regulatory systems, e.g., thermoregulation, involve nervous, endocrine and respiratory functions together. Thus not all physiological systems are localized in one organ.

Thus we can see how sophisticated the present-day study of functions_1, i.e., physiology, has become. It is a far cry from Hippocrates' idea of the blending of the four humors. Present-day physiology represents a break from classical physiology and owes its sophistication to men like Claude Bernard and Walter Cannon, who developed concepts of biochemistry and self-regulation and applied them to living phenomena.

The Informal Definition of 'Function$_1$'

In this final section of this chapter we will state an informal definition of function$_1$. This definition will constitute our explicandum. It will represent a clarification of the pre-systematic term 'function' and an expression of the actual usage of current physiologists, based upon our findings in the previous sections of this chapter.

We will proceed by giving a few instances, some negative and some positive, of function$_1$. Then the informal definition will be stated.

A few cases of processes that are not regulated will help to sharpen the concept we have in mind. The processes whereby chemical equilibria are reached are an example. In the system:

$$HCl + NaOH \rightleftharpoons NaCl + H_2O$$

the more acid is added to the left side of the equation, the more the point of equilibrium shifts to the right. Thus the reaction changes with the change in input. There is thus no self-regulation.

Another case would be that of "passive regulation," i.e., in a thermos bottle (dewar flask). Here we have a variety of environmental conditions with a stable internal condition, due to the insulation of the thermos bottle. But since we have no active compensation for error, no negative feedback, we do not have the process of self-regulation. In fact, a thermos bottle is not designed to meet a variety of conditions, rather, it is designed for one environmental situation. It is designed to maintain a gradient between a warm exterior and a cool interior, or vice-versa.

Instances of the functions studied by physiology today are provided in the following two cases. First, the function$_1$ of liquid waste excretion or regulation of osmolarity, and secondly, the function$_1$ of blood pH maintenance are studied. This latter is a combination of the traditional processes of circulation and respiration.

When the blood passes through the nephrons in the kidney, some elements in the plasma are filtered out. This filtrate then travels through the tubule system of the nephron where some water is reabsorbed from it making it more concentrated; also more elements are secreted into the tubule from the blood vessels which surround this tubule. The resulting liquid is then carried through the ureter and discharged from the body. This is the traditional way of viewing the function$_1$ of excretion (or kidney function, as it is even more traditionally called). Contemporary physiology has shown this to be highly inadequate and incomplete a view of the process. Inadequate because of its lack of formal models, incomplete because the other parts of this process, e.g., regulation of osmolarity, are omitted. It is the regulatory aspect of living processes which provides physiology with a new conceptual framework with which to interpret living processes. The liquid matrix of the body, i.e., the plasma of the blood and the fluid surrounding body tissues is maintained at a constant osmotic pressure. The osmotic pressure represents the concentration of extracellular solutes. Now this constancy is maintained in the face of (1) intake of varying salt concentration; (2) loss of water by evaporation, etc., resulting in varying increase in concentration. Now this process or regulation of osmolarity is in fact the same process as the excretion of liquid waste. The manner of regulation is that changes in fluid concentration are compensated for by changes in fluid volume, i.e., if the concentration becomes high, the volume is increased, thus diluting the concentration and returning it to normal. If the concentration decreases, the volume is decreased, thus increasing the concentration and returning it to normal. Thus by controlling the amount of water excreted, the fluid volume is controlled and thus the osmolarity of the fluid is regulated (see Figure 1).

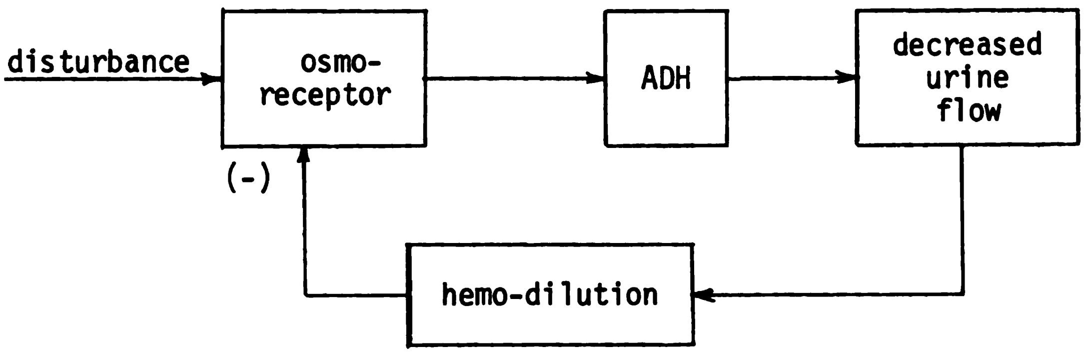

Figure 1. Osmoregulation.

The osmoreceptor, located in the hypothalamus, responds to changes in the osmotic concentration of the extra-cellular fluid. It sends its message for the production of anti-diuretic hormone (ADH) to the posterior pituitary. The ADH travels in the bloodstream to the kidneys where it controls the flow of urine (and thus the volume of extra-cellular fluid). This is a clear example of a physiological function[1] interpreted as a biochemical process regulated by negative feedback.

The extra-cellular fluid can be viewed as a pool, P, of material to be regulated. Disturbances, D, to this pool will cause it to change. The kidneys exert a control, C, on this change by compensating via changes in fluid volume. In other words, disturbances to the pool are compensated by the control (see Figure 2).

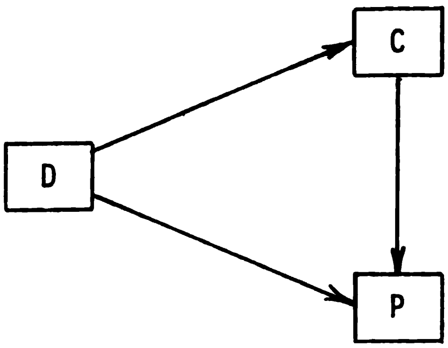

Figure 2. Pathways of control.

The second case is the function[1] of respiration and the regulation of the pH of the blood. From the traditional viewpoint CO_2 in the blood stimulates more rapid breathing thus "blowing off" the excess CO_2 and returning the CO_2 level to normal. However this process is also the process in which the acid level, i.e., level of hydrogen ion concentration, or pH, is regulated. If an acid substance is added to the bloodstream it combines with sodium bicarbonate according to the following equation:

$$HCl + NaHCO_3 \rightleftharpoons NaCl + H_2O + CO_2$$

It can be seen how the hydrogen becomes a part of the water formed, in addition, salt, a neutral compound is formed, and CO_2 is also formed. CO_2 signals the respiratory center and breathing becomes active and the CO_2 is blown off. The pH of the blood is then returned to normal. The amount of increased breathing is controlled by the amount of excess CO_2, which is controlled by the amount of increased acid component, and thus the pH of the blood is regulated (see Figure 3).

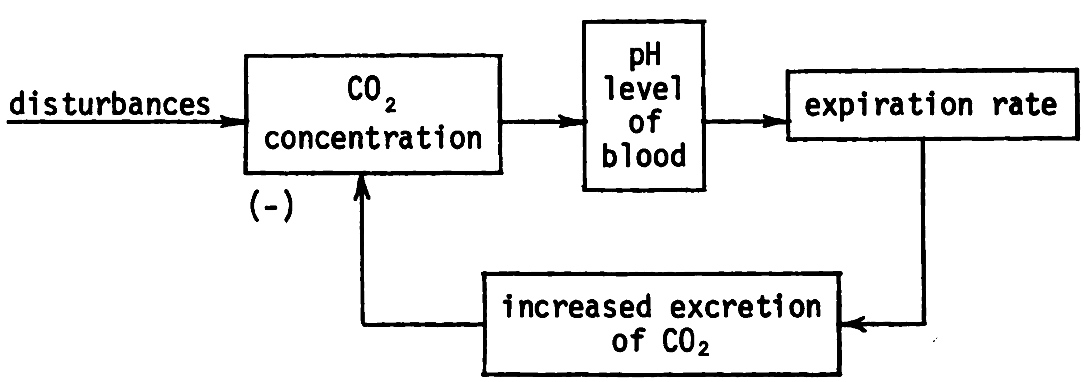

Figure 3. pH regulation.

The following conditions summarize what has been learned about the physiological concept of function. Together they constitute an informal definition of the explicandum.

> Condition 1. *The function is a process, i.e., a spatio-temporal structure.*

This is the categorial condition. It states that $functions_1$ are entities of the material, i.e., spatio-temporal, universe. Given that "purposes" and "utilities" are not spatio-temporal, they are ruled out by this condition. The inclusion of the temporal aspect also accounts for the "dynamic" connotations of the term 'function.' In fact, bio-chemical substances and their changes over time are the entities that are considered by physiologists today to constitute $functions_1$. This condition captures that fact.

> Condition 2. *The process can be described in terms of "black boxes," i.e., systems, each consisting of an input, output, and transfer function.*

This condition specifies the formal structure of the process mentioned in Condition 1. This condition permits the application of the formal and mathematical techniques of the analysis of systems which physiologists and bio-engineers use in their work.

> Condition 3. *The output is relatively stable, i.e., relative to the input.*

This is the steady-state condition. This condition captures what other writers have called the 'goal-directed' aspect of living phenomena. Here we have the phenomenon that Claude Bernard noticed, i.e., the disturbances in the external environment are not transmitted to the interior of the organism. This condition is the important one for quantitative measurement of self-regulation also. To the extent that a system can keep its output stable, i.e., the smaller the ratio of output change to input change, the better that system "functions," i.e., the better self-regulator it is.

> *Condition 4*. *A mechanism of active compensation, directed by the input, is used to control the relative stability of the output.*

This condition differentiates active self-regulation from passive self-regulation. It is not just blockage of the input variety, but an active compensation for it that marks the living self-regulating systems studied by physiology.

The above four conditions constitute the conditions of adequacy which any formal explicatum must meet. In the following chapters we shall construct an explicatum on the basis of this explicandum, i.e., as it is defined by these four conditions.

CHAPTER THREE

THE TRANSMISSION OF VARIETY: FORMAL PRINCIPLES

Introduction

Our discussion of the method of explication in the first chapter pointed out that the second phase of an explication consists of the construction of a formalized concept, one that corresponds to the explicandum but is defined in terms of some formal system. This chapter provides the formal system which will be used, in the next chapter, to formulate such an explicatum for the physiological concept of function. We will outline here the general principles needed to describe what we call the "transmission of variety." We will not attempt to provide a comprehensive treatment of this topic. While we will discuss all of the foundational concepts, the details of the discussion will be restricted to those that will be useful in formulating our desired explicatum.

In setting up a formal system, an interpretation is essential. Otherwise, the formal structure remains idle. It is the interpretation of the formal system which ties the explicatum to the subject matter of the explicandum; it is a necessary condition for a relevant explication. We referred to it in Chapter One as the "systematic context." Carnap emphasizes this point in connection with his explication of the concept of probability.

> Some authors believe they have given a solution of the problem of probability, in our terminology, an explication for probability, by merely constructing an axiom system for probability without giving an interpretation; for a genuine explication, however, an interpretation is essential.[1]

In this chapter then, we will be doing two things. First, we will be setting up the formal structure. This will consist of the mathematical structure of what is usually termed "information theory." Secondly, we will be interpreting this mathematical structure in terms of spatio-temporal processes. While the mathematical structure is straightforward and widely used, the interpretation provided here will be somewhat different from the usual interpretations.

The mathematical structure we will set up in this chapter was originally developed as part of what is known as "information theory" or "communication theory." The practical context in which this information theory developed was that of communication devices. In particular, problems in telegraphy, telephony, and teletype communication systems were providing the stimulus to a more rigorous, i.e., mathematical, approach in solving these problems. Encoding English letters into electrical pulses, for example, raised the problem of finding an efficient encoding procedure. To provide a mathematical foundation for answering such questions, Claude E. Shannon published an article in 1948 in the Bell System Technical Journal.[2] In his article, Shannon was

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[1]Rudolf Carnap, Logical Foundations of Probability (Chicago: University of Chicago Press, 1962), p. 16.

[2]Claude E. Shannon, "A Mathematical Theory of Communication," Bell System Technical Journal, XXVII (1948), 379-423, 623-656.

dealing explicitly with communication, i.e., the transmission of symbols which are used as carriers of messages.

In spite of the recognition of many authors of the universality of information-theoretical ideas, and in spite of the wide range of applications of information theory, the theory has not yet shed its original cognitive interpretation. For example, the measurement of information is usually interpreted as its "surprise" or "news" value, i.e., the extent of surprise or degree of unexpectedness. The measurement is based upon the probabilities attached to the symbol or group of symbols in question. In other words, if some event having a low probability of expected occurrence does occur, we are given more "information" than if an event having a high probability of expected occurrence would occur. Information is thus inversely proportional to the expected probability. To receive the message that the sun did not rise today is to receive much more "information" than that obtained from the message that the sun did rise today. The former is much more improbable than the latter, and thus conveys more "information," although, it might be noted, as far as "reporting facts," both messages are the same.

The interpretation of probabilities as measures of "unexpectedness" or " uncertainty" shows that these interpretations are modeled on human cognitive activities. Leon Brillouin, for example, has said; "We define 'information' as the result of a choice."[3] Brillouin is here stating that "information" is not to be taken as equivalent to

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[3]Leon Brillouin, Science and Information Theory (New York: Academic Press, 1962), p. 9.

"knowledge"; it is not a basis for choice, but rather it refers to the _result_ of a choice. Thus while disclaiming that "information" is equivalent to "knowledge" or "report of facts," he still interprets it as a factor resulting from human cognitive or volitional processes.

More evidence for the exclusively cognitive or psychologistic interpretation of information measures is provided by the prevalence of the view that language is the chief carrier of information. "Most of the information we use is communicated by means of the language."[4] Thus a major part of any discussion of information theory in the literature about it deals with encoding and decoding of languages. As we mentioned earlier, this was the original interpretation used by Shannon; and it still remains the predominant interpretation of information theory.

And in looking at the applications of information theory in the biological sciences, we find that they are almost entirely restricted to models of the brain and corresponding types of nervous processes. This again reflects the emphasis on cognitive applications of information theory.

But there are other ways to interpret the mathematical structure of what is called "information theory." An economist, Henri Theil, has said this about information theory:

> Although most of the results are still in the field of communication theory in the narrow sense, there are several applications in other areas ranging from statistics to psychology. . . . The reason information theory is

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[4] _Ibid_., p. 4.

> nevertheless important in economics is that it is more than a theory dealing with information concepts. It is actually a general partitioning theory in the sense that it presents measures for the way in which some set is divided into subsets. . . .[5]

We propose, then, to forego the usual cognitive interpretation and interpret probabilities in terms of physical processes, i.e., spatio-temporal structures. This should have at least salutary effects. First it should show that it is possible to interpret probabilities and probability correlations in other ways than cognitive. Secondly, it should provide us with an interpretation of a formal structure which we can apply in our explication of the physiological concept of function. And this will result in precise new insights into physiological processes. In particular, the probabilistic character of physiological processes, many of which are controlled by hormones and other chemical substances which give the system a reliable but not perfect system of transmission, is captured by the probabilistic character of the theory of variety.

In the following pages, basic concepts of probability will be introduced. These will be interpreted in terms of 'disturbance' and 'variety.' Then the transmission of variety will be treated in a mathematical way. Throughout this discussion we will sometimes refer to cognitive interpretations insofar as they are helpful in presenting the ideas concerning 'disturbance' and 'variety.'

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[5]Henri Theil, Economics and Information Theory (Chicago: Rand McNally & Company, 1967), p. 19.

Probability Concepts

The fundamental concept used in our theory is that of the probability of an event, and this section will outline the necessary principles of probability theory. In a sample space $\{e_1, e_2, \ldots, e_n\}$, a probability $P(e_i)$ will be assigned to each possible outcome e_i, such that

(1) $\sum_{i=1}^{n} P(e_i) = 1$

(2) $0 \leq P(e_i) \leq 1.$

By 'probability of an event' we mean the relative frequency of the event.[6] A certain occurrence is probable because it is frequent. Rain is probable in April because it is frequent in April. The test for a constant probability thus becomes a test for a constant frequency. The experimenter continues to observe until some frequency for the event becomes evident.

More specifically, the relative frequency of an event of type x is given as the number of elements in a reference class R having the property x, divided by the number of elements in R. For example, the relative frequency of rainy days can be given by the number of days in the year on which it rained divided by the number of days in the year. Then the probability of x is the relative frequency of x in the limit, i.e., as the number of elements in R approaches infinity.

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[6]There are other notions of probability which are equally useful, and which can be used to formulate a systematic treatment of information and variety. However, the treatment of probability concepts will be limited to the essentials necessary for use in our explication of 'function.'

This mode of probability assignments has various characteristics. First, statements of probability predicate something of an individual only insofar as it is an element in a specified reference class. Secondly, probability statements are empirical statements. The direct evidence for them is of a statistical nature, although estimation of numerical values of probabilities may be made on the basis of indirect evidence. Since we are dealing with an empirical concept in our explication, the concept of function_1, the use of this relative frequency approach is most fruitful. The data from empirical studies in physiology can be used with our concept, and interpreted as patterns of self-regulation.

The standard calculus of probability is the basis for our principles. The probability of the simultaneous occurrence of two independent events is the product of their individual probabilities. And if two events are mutually exclusive, the probability that one or the other will occur is equal to the sum of their individual probabilities.

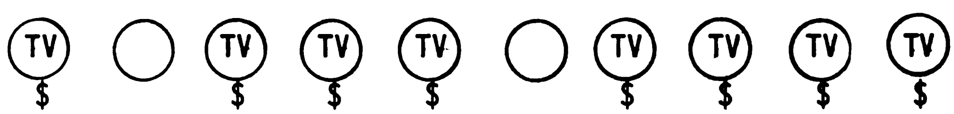
The joint probability of two events, $P(e_i,f_j)$, and the conditional probability of two events, $P(f_j/e_i)$, i.e., the probability of f_j given e_i, can be related in terms of the following equation:

$$P(e_i,f_j) = P(f_j,e_i) = P(f_j)\ P(e_i/f_j) = P(e_i)\ P(f_j/e_i) \qquad (1)$$

As an example, consider a town composed of 10 households. Let $P(e_i)$ represent the probability that the i-th household has a television, and let $P(f_j)$ represent the probability that the j-th household has an annual income of over \$10,000. Now assume that 8 households have televisions, thus $P(e_i) = 0.8$, and that 8 households earn more than \$10,000 annually, thus $P(f_j) = 0.8$. Now suppose that a household earns more than \$10,000 annually. What is the probability that they also own a television?

$$P(e_i/f_j) = \frac{P(e_i,f_j)}{P(f_j)} \tag{2}$$

If every household that has a television is also a household that earned over \$10,000 annually, then $P(e_i,f_j)$ would be 0.8 and $P(f_j)$ would be 0.8 and thus $P(e_i/f_j) = 1.0$. Thus there is a 100 percent probability that the household has a television, given that it earns over \$10,000 annually. Figure 4 illustrates this situation.



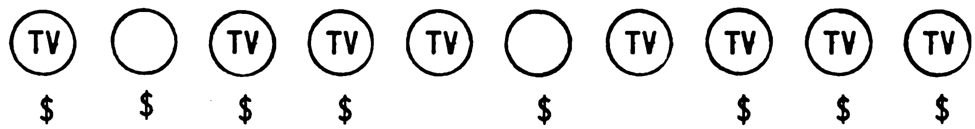
TV = has a television
\$ = earns over \$10,000 annually

Figure 4. Television ownership and income.

Notice that we can also calculate the joint probability, given the conditional probability.

$$\begin{aligned} P(e_i,f_j) &= P(f_j)\ P(e_i/f_j) \\ &= 0.8 \times 1.0 \\ &= 0.8 \end{aligned} \tag{3}$$

Now suppose that some households own a television and do not earn over \$10,000 annually, and vice-versa. See Figure 5 for such a situation.



TV = has a television
\$ = earns over \$10,000 annually

Figure 5. Television ownership and income.

Based on Figure 5, we would calculate the conditional probability of a household having a television given that it earned over \$10,000 annually as follows:

$$P(e_i/f_j) = \frac{P(e_i,f_j)}{P(f_j)} \tag{2}$$

$$= \frac{0.6}{0.8}$$

$$= 0.75$$

Thus with Figure 5 there is a 75 percent chance that a household will have a television, given that it earns over \$10,000 anually. Again notice that if we were given the conditional probability, we could calculate the joint probability.

$$P(e_i,f_j) = P(f_j)\ P(e_i/f_j) \tag{3}$$

$$= 0.8 \times 0.75$$

$$= 0.6$$

The probability concepts outlined above will be all that is needed to set up the basic principles of our theory of variety, as far as we will be using it in this dissertation. Obviously, more detailed treatment is possible and more complex topics have been elaborated by probability theorists. We will not discuss these in this chapter.

Disturbance Sources

The term 'disturbance,' when used in the context of physical processes, is associated with a change in the value of some state, which change causes a change in value of some other state. If a man is sleeping, a disturbance is a physical process, e.g., a noise, which changes the state of the man from sleeping to waking. If a body is traveling in a straight line, a disturbance is a force which would result in a change in the direction and/or velocity of that body. In other words, a disturbance is a specified value of a state variable with a view toward what that value does, i.e., its effect.

Now the effectiveness of a disturbance x_i depends upon the probability, i.e., the relative frequency, of that state x_i. If a state x_i always occurs, i.e., has a probability of 1, then it produces no disturbance. If it is extremely rare, i.e., improbable, its occurrence causes a large disturbance. Tidal waves are rare and when they occur they produce a large disturbance; this is mainly due to lack of preparedness, or compensating ability, of shoreline installations. In the context of living systems, rare occurrences, i.e., disturbances, can take the system out of its normal condition. It is the mechanism of self-regulation which compensates for these disturbance.

The disturbance of an event then, is inversely proportional to the probability or directly proportional to the improbability of that event. Where e is an event, then the disturbance, d, of e is given by

$$d(e) = \log_2 \frac{1}{P(e)} \tag{4}$$

The reason for including a logarithm in the formula will be discussed presently.

A disturbance-generating mechanism is described as a "source." In generating disturbances, a source emits a sequence of states from a finite, fixed set of states $X = \{x_1, x_2, x_3, \ldots x_q\}$. This process of generating disturbances has various properties and the present section will show some of these properties.

The generation of disturbance-producing states occurs by a process called a "Markov process." We define a Markov source as a source in which the occurrence of a state x_i depends upon a finite number, m, of preceding states. Such a source is called an m-th order Markov source, and is specified by giving the set of states X and the set of conditional probabilities

$$P(x_i/x_{j_1}, x_{j_2}, \ldots, x_{jm}) \text{ for } i = 1,2,\ldots,q;\ j_p = 1,2,\ldots,q$$

For an m-th order Markov source, the probability of emitting a given state is known if we know the m preceding states.

Note that a Markov source can be either probabilistic or deterministic. In the latter case the conditional probabilities for each x_i are eith 0 or 1.

In dealing with m-th order Markov sources we shall restrict ourselves to what are referred to as "ergodic" sources. An ergodic source is a source which, if observed for a very long time, will (with probability 1) emit a sequence of states which is typical. The statistics of the sequences of states do not change with time; that is, the source is stationary. A further property of ergodic Markov source is that the probability distribution over the set of sequences which appears after many transitions does not depend upon the initial distribution with which the sequences are chosen. The principles of variety theory which we assume will all refer to ergodic Markov processes as described above.

The m-th order Markov source is called a "zero-memory" or "memoryless" source when successive states emitted from the source are statistically independent, i.e., $m = 0$. Such a source is completely described by the set of states X and the probabilities with which the states occur:

$$P(x_1),\ P(x_2),\ \ldots,\ P(x_q)$$

The source may be either discrete or continuous. A discrete source produces a sequence state by state, using discrete values, rather than producing a signal such as an electrical signal, which varies continuously and may have any value at a given time. The signals from a continuous source can be treated by the use of the <u>sampling theorem</u>. This is a mathematical theorem which states that a continuous signal can be represented completely by and reconstructed perfectly from a set of measurements or "samples" of its range which are made at equally spaced times. The interval between such samples must be equal to or less than one-half of the period of the highest frequency present in the signal.

Throughout this dissertation we will be dealing with discrete sources only. That this presents no problems or objections to our treatment can be seen by considering the following two points. First, continuous signals can be represented by discrete samples. Secondly, observations of natural phenomena are always made at discrete intervals; the "continuity" ascribed to natural events has been put there on the basis of some mathematical or theoretical context, e.g., the real number system, and not by actual observation at each of an infinite number of points. Thus actual measurements, which will be considered later in our explication, are discrete, and may with no theoretical difficulty have probabilities applied to them.

The discrete memoryless source which is also an ergodic Markov process will be the basis on which the treatment of the principles of variety theory in this chapter will be based. In particular, formula (6) below will be the definition of the "variety" of such a source.

In the previous chapter, we emphasized the fact that for contemporary physiologists since Claude Bernard, "functions" consist of biochemical processes. This fact provides the motivation for construing probabilities as physical processes, i.e., states, and disturbances as related to the probability of any particular state.

If we couple three sources together, say generators of heat, humidity, and pressure, with each source having $q = 2$, e.g., hot, cold; dry, wet; high, low; we have 8 possible different combined states ($2 \times 2 \times 2$). Examples would be hot, dry, and high; hot, dry, and low; etc. However it seems more natural to expect the amount of disturbance of the combination to be the sum of the disturbances of the individual sources, not the product, i.e., by increasing the number of states you are adding to the disturbance potential. We can formulate a measure which satisfies this expectation if we have recourse to logarithms; with these we transform products into sums. Thus by choosing to measure the disturbance of each source by log 2 instead of 2, we ensure that the disturbance of the complex of the three sources is the sum of their individual components. This appeal to intuition is not the major reason for using the logarithm in our definition of variety. There are properties of the logarithm which make its use even more plausible. For example, the logarithm of 1 is 0. Thus with only one value of some state, we have a variety of 0. Also, as the probabilities of a set of states become equally distributed, the greater is the variety. Again, the logarithm measure would show this. Examples will be given in the next few pages of the importance of this latter property.

The number 2 seems an obvious choice as a base for the logarithm because it is the minimum number of disturbance states that the most rudimentary system would have. Thus a disturbance source with two equally likely alternatives has $\log_2 2 = 1$ unit of disturbance. Such units we will call 'bits,' a contraction of 'binary units.'

Thus the average amount of disturbance per state of a source with q equiprobable states is given by

$$V(X) = \log_2 q \text{ bits per state} \qquad (5)$$

This formula defines the 'variety' of the source, i.e., the measure of the average disturbance potential per state of that source.

Formula (5) however is for the special case where the states are equiprobable. In the more general case this does not hold. The variety of a source changes if each of the possible choices in it is not equiprobable. Thus if in the case of our generators above, the hot state occurs nine times as often as the cold, then the disturbance produced by the hot state is

$$\log_2 \frac{1}{0.9}$$

and by the cold state is

$$\log_2 \frac{1}{0.1}$$

The total variety of the system is the sum of the two components, each contribution being "weighted" by its own probability, i.e.,

$$0.9 \log_2 \frac{1}{0.9} + 0.1 \log_2 \frac{1}{0.1} = 0.476 \text{ bits}$$

The general formula then for variety, i.e., the average amount of disturbance, is as follows:[7]

$$V(X) = \sum_{X} P(x_i) \log_2 \frac{1}{P(x_i)} \text{ bits per state} \tag{6}$$

The consequences of having unequal probabilities attached to the states are very important. "Every type of constraint, every additional condition imposed on the possible freedom of choice immediately results in a decrease of information."[8] Thus in our example of a single temperature generator, if we have two equiprobable alternatives, x_1 and x_2, i.e., hot and cold (with $q = 2$), then the variety of this source X is given by formula (5):

$$\begin{aligned} V(X) &= \log_2 q \\ &= \log_2 2 \\ &= 1 \text{ bit} \end{aligned} \tag{5}$$

If the hot state occurs nine times as much as the cold, then a constraint is put upon the source X, and the variety is given by formula (6):

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[7]Some authors, including Shannon, formulate (6) as

$$H(X) = - \sum_{X} P(x_i) \log_2 P(x_i)$$

There is no real difference between the two formulations, since $\log \frac{1}{x} = -\log x$. I use the logarithm of the reciprocal of the probability, rather than the negative of the logarithm of the probability because the logarithm values are easier to calculate using the former formulation.

[8]Brillouin, <u>op. cit</u>., p. 8.

$$V(X) = \sum_{X} P(x_i) \log_2 \frac{1}{P(x_i)} \tag{6}$$

$$= 0.9 \log_2 \frac{1}{0.9} + 0.1 \log_2 \frac{1}{0.9}$$

$$= 0.476 \text{ bits}$$

The variety of the source has decreased by more than half.

Now there is a close analogy between the above discussion of variety and state probabilities, and the more traditional interpretation of "information theory." If one replaces our 'states' by 'symbols' and our 'disturbance' by 'reduction of uncertainty,' i.e., 'information,' this analogy is quite visible. An excellent example, then, of the effect of constraints upon the variety of the source is given by the English language. We can assume there are 27 symbols (26 letters and one space) in this source, which, according to formula (5) would have an average "information" of

$$H(X) = \log_2 q \tag{7}$$

$$= \log_2 27$$

$$= 4.76 \text{ bits}$$

However, there are in fact constraints upon the occurrence of these letters, some letters, e.g., 'e,' 't,' 'a,' and 'c' occur much more frequently than others, e.g., 'z,' 'x,' 'y,' and 'q.' If we assign each letter its correct probability of occurrence, which has been determined empirically, we can determine the average amount of information of the source, the English alphabet, as it is found in fact.

$$H(X) = \sum_{X} P(x_i) \log_2 \frac{1}{P(x_i)} \tag{8}$$

$$= 4.03 \text{ bits}$$

The decrease in average information is apparent.

The basic properties of our definition of variety are thus as follows:

1. If a set of occurrences is broken down into two constituent subsets of occurrences, then the amount of variety is the weighted sum of the amounts of variety in each subset of occurrences.
2. The variety of a source is a maximum when all of the probabilities are equal. That is, for a zero-memory source X, with states $\{x_1, x_2, \ldots, x_q\}$, the maximum value of the variety of the source is exactly $\log_2 q$, and this maximum value is achieved if and only if, all the source states are equiprobable.

Our definition of 'variety' is closely related to the physical concept of entropy. Shannon uses the term 'entropy' to describe his concept of "average amount of information," which he represents by 'H(X).' "The form of H will be recognized as that of entropy as defined in certain formulations of statistical mechanics where p_i is the probability of a system being in cell i of its phase space."[9] The famous Boltzmann-Planck formula for entropy, S, is given as:

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[9]Claude E. Shannon and Warren Weaver, The Mathematical Theory of Communication (Urbana: University of Illinois Press, 1949), p. 20.

$$S = k \log_e P \tag{9}$$

where k is Boltzmann's constant ($k = 1.38 \times 10^{-16}$ ergs per centigrade degree), and P is the number of "elementary complexions." P is explained by Brillouin as follows: "Each of these discrete configurations of the quantized physical system was called a "complexion" by Planck, and the word has remained in the scientific literature with this well-defined meaning."[10] Thus the statistical interpretation of entropy by physicists seems to be the same as what we are calling 'variety,' with the exception that the set of possible occurrences are quantum configurations for physicists while the definition of 'variety' refers to any set of distinguishable occurrences, microscopic or macroscopic. This captures the notion of variety very precisely. Thus in statistical mechanics, entropy is interpreted as a decrease in order or an increase in the amount of disorderliness, i.e., variety.

What we are proposing in this chapter then is a physical interpretation of what is usually termed 'information' and given a cognitive interpretation. This is not to say that physiological processes could not also be given this cognitive interpretation. One can view the effect of environmental factors on internal processes of an organism as a type of encoding. More precisely, one could employ the notion of a transducer, e.g., a machine which converts mechanical energy into electrical energy. A transducer works through encoding one energy form into another. In living organisms too, heat energy may be encoded into

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[10]Brillouin, op. cit., p. 120.

glandular activity, i.e., sweating, to produce regulation of body temperature. We could interpret this process as involving "communication," i.e., that the organism "perceives" disturbances in the environment and "chooses" the appropriate counteraction. However, these interpretations are more appropriate in the context of conscious processes. While human processes can be interpreted in this way, physiology studies organisms of all types. Given, then, that most of the organisms studied by physiologists are not conscious, e.g., dogs, cats, etc., and that the individual processes, even in humans, e.g., circulation, respiration, are at the non-conscious level, then it would seem more appropriate to speak of the regulation of "variety," rather than "information."

The measures given in formulas (5) and (6) can be seen to measure variety, by the help of a few examples. Suppose we consider a deck of 64 different cards and a deck of 16 cards. The first deck, with $q = 64$, has a variety of

$$\begin{aligned} V(X) &= \log_2 q \qquad (5) \\ &= \log_2 64 \\ &= 6 \text{ bits} \end{aligned}$$

The second deck, with $q = 16$, has a variety of

$$\begin{aligned} V(X) &= \log_2 q \qquad (5) \\ &= \log_2 16 \\ &= 4 \text{ bits} \end{aligned}$$

Thus the first deck has more variety than the second.

Consider the question of whether Michigan or Puerto Rico has a greater variety of weather (let us assume temperature as the only factor). Comparing the two in degrees Fahrenheit, we see Michigan, assuming an annual range of from -20°F to 95°F has a variety of

$$\begin{aligned} V(X) &= \log_2 q \qquad\qquad (5) \\ &= \log_2 115 \\ &= 6.84 \text{ bits} \end{aligned}$$

Puerto Rico, assuming an annual range of 55°F to 100°F has a variety of

$$\begin{aligned} V(X) &= \log_2 q \\ &= \log_2 45 \\ &= 5.49 \text{ bits} \end{aligned}$$

Using formula (5) of course assumes an equal distribution of each disturbance, i.e., temperature change. Two regions may also have the same temperature range but different distributions of it. Consider region A and region B, both having annual temperature ranges of 32°F, say from 21°F to 52°F. If these temperatures occurred with equal distribution in both regions, then the variety of both would be

$$\begin{aligned} V(X) &= \log_2 q \qquad\qquad (5) \\ &= \log_2 32 \\ &= 5 \text{ bits} \end{aligned}$$

We would say that that the temperature in both regions has an equal amount of variety. Suppose, however, that in region B the warmer temperatures, say from 37°F to 52°F occurred approximately three times as often as the cooler temperatures, 21°F to 36°F. The probability of a day having a temperature in the cooler range thus being $\frac{1}{64}$ and in the warmer range being $\frac{1}{21}$. We would intuitively say that there was not as much variety in the temperature in region B. It would tend to have warmer weather, as compared to region A, which has more of a variety. This decrease of variety found in region B can be calculated as follows:

$$V(B) = \sum_{x} P(x_i) \log_2 \frac{1}{P(x_i)} \tag{6}$$

$$= 16 \times \frac{1}{64} \log_2 \frac{1}{64} + 16 \times \frac{1}{21} \log_2 \frac{1}{21}$$

$$= 16 \times .094 + 16 \times .209$$

$$= 4.86 \text{ bits}$$

The fundamental importance of the concept of variety has been emphasized by E. F. Adolph, a physiologist who devoted a lifetime to the study of general patterns and concepts of physiological regulation.

> The physiological significance of variation in content is, I believe, that the limitation of the variations measures the maintenance of that content. Whenever content tends to change, activities on the part of the organism intervene to oppose the change. If this could be said in mathematical language alone, many possible misunderstandings would be avoided.[11]

Adolph shows that the regulation in physiological systems works on "variations," i.e., variety. And in particular that a stable system, i.e., one having a "limitation of the variations" is due to environmental

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[11]E. F. Adolph, Physiological Regulations (Lancaster, Pa.: Jaques Cattell Press, 1943), p. 77.

variety being compensated for by opposite variety. This is what W. Ross Ashby calls the "Law of Requisite Variety," i.e., "only variety can destroy variety."[12] Now what Adolph is asking for is a quantitative concept of physiological regulation, in terms of variety. It is this which will be provided in Chapter Four of this study.

Reproduction of Variety: Channels

We have viewed disturbance sources in terms of their variety. Now the "consequences" or "effects" of disturbances can also be discussed mathematically. We do this by considering the disturbance as traveling over a channel. The disturbance or input is related to the effect or output by means of a channel through which the variety is reproduced to some degree or another. The input can also be viewed as a "transmitter" of variety and the output as a "receiver" of variety. With an ideal channel, any input variety is faithfully reproduced at the output, i.e., the transmitted variety is equal to the received variety. This notion of a channel is represented in Figure 6.

$$\boxed{\text{transmitter}} \longrightarrow \boxed{\text{channel}} \longrightarrow \boxed{\text{receiver}}$$

Figure 6. A channel.

More complex networks may be constructed of a number of channels.

[12] W. Ross Ashby, An Introduction to Cybernetics (London: Chapman & Hall, 1956), p. 207.

Now, the transmission of variety in the formal or theoretical sense, in contrast with the concrete sense mentioned above, is defined solely in terms of a set of input states, a set of output states, and a set of conditional probabilities for these states (see Figure 7). The conditional probabilities $P(y_j/x_i)$, are called the "transition probabilities" of the channel.

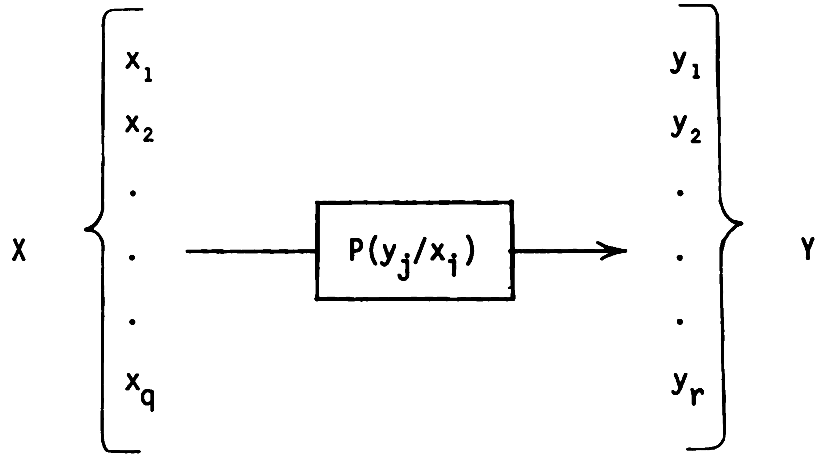

Figure 7. Definition of a channel.

Now a perfect channel is called a "noiseless" channel. Consider a channel having a source set $X = \{x_1, x_2, x_3, x_4\}$ and a receiver set $Y = \{y_1, y_2, y_3, y_4\}$ in which the transition probabilities $P(y_j/x_i) = 1$; for each x_i transmitted, one and only one y_j is received. A state-diagram representing this noisless channel is shown in Figure 8.

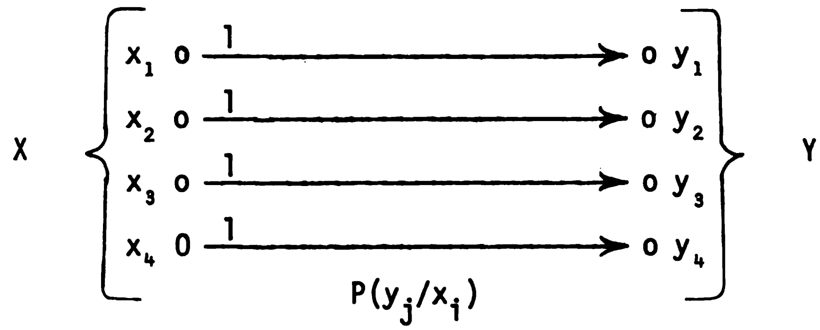

Figure 8. A noiseless channel.

Now there are two variations in this pattern of variety reproduction. The first variation, called a "lossless" channel, is one in which given any y_j, we know with probability of 1 that a specific x_i was sent. Figure 9 is a state-diagram for this case.

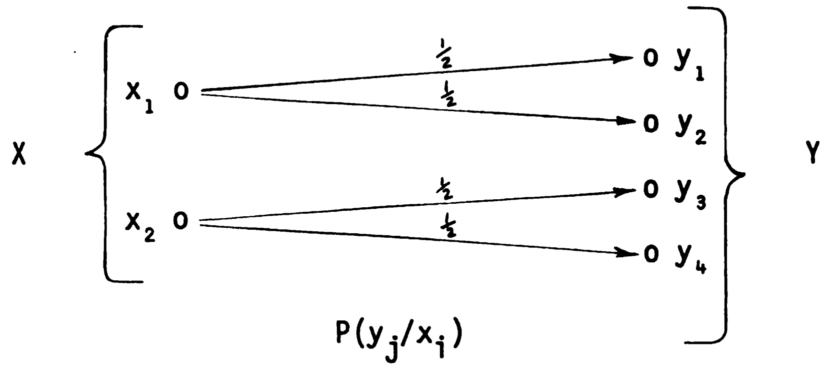

Figure 9. A lossless channel.

Note that with this channel, while nothing has been lost, some variety has been added. The variety of X, is calculated as

$$V(X) = \sum_X P(x_i) \log_2 \frac{1}{P(x_i)} \tag{6}$$

$$= \frac{1}{2} \times 1 + \frac{1}{2} \times 1$$

$$= 1 \text{ bit per state}$$

We have assumed in Figure 6 and Figures 7 and 8 below the simple case where each source state in X has equal probability.

The variety of Y is calculated as

$$V(Y) = \sum_X P(y_j) \log_2 \frac{1}{P(y_j)} \tag{10}$$

$$= \frac{1}{4} \times 2 + \frac{1}{4} \times 2 + \frac{1}{4} \times 2 + \frac{1}{4} \times 2$$

$$= 2 \text{ bits per state}$$

Thus while 1 bit was transmitted, 2 bits were received. This added variety is referred to as "noise," and is calculated with the following formula:

$$V(Y/X) = \sum_{x} P(x_i) \sum_{y} P(y_j/x_i) \log_2 \frac{1}{P(y_j/x_i)} \tag{11}$$

Using the channel shown in Figure 9 we can calculate the noise as

$$V(Y/X) = \sum_{x} P(x_i) \sum_{y} P(y_j/x_i) \log_2 \frac{1}{P(y_j/x_i)} \tag{11}$$

$$= \frac{1}{2} \times \frac{1}{2} \times 1 + \frac{1}{2} \times \frac{1}{2} \times 1 + \frac{1}{2} \times 0 \times 0 + \frac{1}{2} \times 0 \times 0$$

$$+ \frac{1}{2} \times 0 \times 0 + \frac{1}{2} \times 0 \times 0 + \frac{1}{2} \times \frac{1}{2} \times 1 + \frac{1}{2} \times \frac{1}{2} \times 1$$

$$= 1 \text{ bit}$$

Thus V(Y/X) represents variety that comes out of a channel without being put in, it is variety added in transmission. It is called 'noise' with the idea that the irrelevant parts of the output interfere with good control. Thus to find the actual amount of variety transmitted over a channel, we must subtract the noise from the output. The amount of "throughput" variety, i.e., actually transmitted variety is thus given by

$$T(X;Y) = V(Y) - V(Y/X) \tag{12}$$

For the lossless channel shown in Figure 9, we would have

$$T(X;Y) = V(Y) - V(Y/X) \qquad (12)$$
$$= 2 - 1$$
$$= 1 \text{ bit per state}$$

Note that for the noiseless channel shown in Figure 8, the noise would be

$$V(Y/X) = \sum_{X} P(x_i) \sum_{y} P(y_j/x_i) \log_2 \frac{1}{P(y_j/x_i)} \qquad (11)$$
$$= \frac{1}{4} \times 1 \times 0 + \frac{1}{4} \times 1 \times 0 + \frac{1}{4} \times 1 \times 0 + \frac{1}{4} \times 1 \times 0$$
$$= 0$$

(The reader is reminded that $\log_2 1 = 0$)

Since $V(Y) = 2$ bits per state, then the throughput variety is calculated as

$$T(X;Y) = V(Y) - V(Y/X) \qquad (12)$$
$$= 2 - 0$$
$$= 2 \text{ bits per state}$$

A second variation from the perfect channel type is called a "deterministic" channel. In this type of channel the probability that a particular y_j is received given that an x_i was sent is 1. Figure 10 is a state-diagram for such a case.

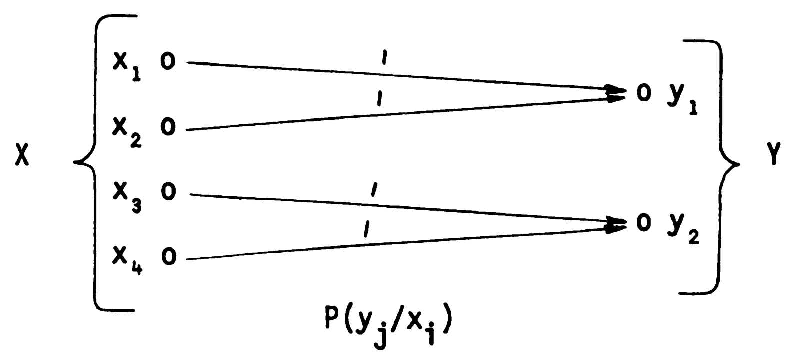

Figure 10. A deterministic channel.

Notice that with this channel while no noise has been added, there has been some loss. $V(X) = 2$ bits and $V(Y) = 1$ bit. Thus while 2 bits are transmitted, 1 bit is received. This lost variety is referred to as 'loss' and is calculated with the following formula:

$$V(X/Y) = \Sigma\, P(y_j)\, \Sigma\, P(x_i/y_j)\, \log_2 \frac{1}{P(x_i/y_j)} \tag{13}$$

Using channel shown in Figure 10 we can calculate the loss as[13]

$$V(X/Y) = \Sigma\, P(y_j)\, \Sigma\, P(x_i/y_j)\, \log_2 \frac{1}{P(x_i/y_j)} \tag{13}$$

$$= \frac{1}{2} \times \frac{1}{2} \times 1 + \frac{1}{2} \times 0 \times 0 + \frac{1}{2} \times \frac{1}{2} \times 1 + \frac{1}{2} \times 0 \times 0$$

$$+ \frac{1}{2} \times 0 \times 0 + \frac{1}{2} \times \frac{1}{2} \times 1 + \frac{1}{2} \times 0 \times 0 + \frac{1}{2} \times \frac{1}{2} \times 1$$

$$= 1 \text{ bit}$$

Thus $V(X/Y)$ represents variety put into a channel but not gotten out, it is variety lost in transmission. To determine the actual amount of variety transmitted we must subtract the loss from the input or source. The amount of "throughput variety," i.e., variety actually transmitted, is given by

$$T(X;Y) = V(X) - V(X/Y) \tag{14}$$

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[13] $P(x_i/y_j)$ is derived using Bayes' Law:

$$P(x_i/y_j) = \frac{P(x_i)\, P(y_j/x_i)}{\sum_X P(x_i)\, P(y_j/x_i)}$$

For the deterministic channel shown in Figure 10 we would have

$$T(X;Y) = V(X) - V(X/Y) \tag{14}$$
$$= 2 - 1$$
$$= 1 \text{ bit}$$

For the noiseless channel shown in Figure 8 the loss would be

$$V(X/Y) = \sum_{y} P(y_j) \sum_{x} P(x_i/y_j) \log_2 \frac{1}{P(x_i/y_j)} \tag{13}$$
$$= \frac{1}{4} \times 1 \times 0 + \frac{1}{4} \times 1 \times 0 + \frac{1}{4} \times 1 \times 0 + \frac{1}{4} \times 1 \times 0$$
$$= 0$$

Since Y(X) = 2 bits for this case, then the throughput variety is calculated as

$$T(X;Y) = V(X) - V(X/Y) \tag{11}$$
$$= 2 - 0$$
$$= 2 \text{ bits}$$

A channel is perfectly reliable, i.e., noiseless, if it is both lossless and deterministic; its loss and noise will equal 0. A channel is lossless if its loss, V(X/Y) = 0 and a channel is deterministic if its noise, V(Y/X) = 0. In all these cases T(X;Y) is greater than 0. There is one other type of channel, which we might call 'useless.' These are channels in which T(X;Y) = 0 for any input distribution. Figure 11 gives state-diagrams for three examples.

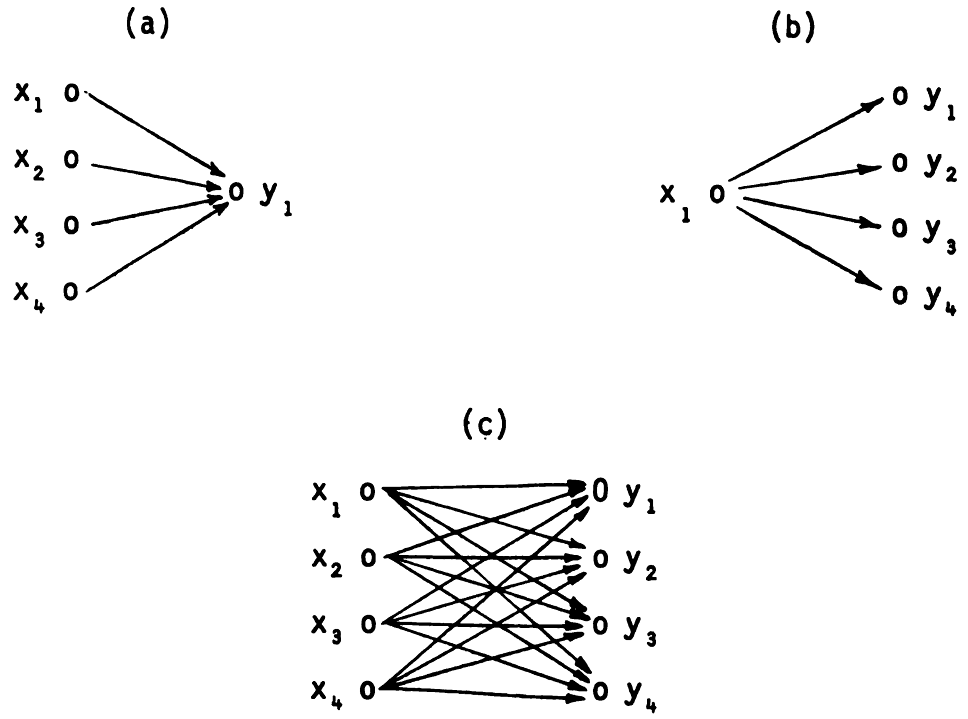

Figure 11. Useless channels.

To calculate the throughput variety for (a) we would have

$$\begin{aligned} T(X;Y) &= V(X) - V(X/Y) \\ &= 2 - 2 \\ &= 0 \end{aligned} \tag{14}$$

In other words, the loss in the channel equals the variety sent from the source. Likewise with (b) we have

$$\begin{aligned} T(X;Y) &= V(Y) - V(Y/X) \\ &= 2 - 2 \\ &= 0 \end{aligned} \tag{12}$$

The variety at the output was not actually sent; it was added during transmission. Thus the channel, like (a) actually reproduces no variety.

Example (c) also shows a useless transmission channel. The loss in this case would be calculated as

$$V(X/Y) = \sum_{y} P(y_j) \sum_{x} P\ (x_i/y_j)\ \log_2 \frac{1}{P(x_i/y_j)} \tag{13}$$

$$= 16 \times \frac{1}{4} \times \frac{1}{4} \times 2$$

$$= 2$$

The actual variety transmitted would be calculated as

$$T(X;Y) = V(X) - V(X/Y) \tag{14}$$

$$= 2 - 2$$

$$= 0$$

The actual rate of transmission over a channel has been shown to be represented by T(X;Y). This is the actual rate in bits per state. If the transmission rate of states per unit time is known, then the actual rate can be stated in terms of bits per unit time, e.g., bits per second. Now the examples we used all had an equiprobable distribution of input or source states. This is not always the case with variety sources, and with less equiprobable distributions the actual rate of throughput variety would have changed. Thus, the rate of transmission over a channel depends on the probability distribution of the source states. On this basis we can define the channel "capacity" as the maximum possible rate of transmission for a channel. The actual calculation of a channel capacity, except for very simple channels, is highly complicated, and will not be discussed any further here. The use of the actual rate of transmission, T(X;Y) is adequate for the purposes of the explication in this dissertation.

It also must be remembered that the actual rate of transmission is calculated only for discrete memoryless channels. Again, for the purposes of the explication in this dissertation, this restriction is in no way detrimental.

Channels in Cascade

In this section we will consider the principles governing the cascade of two channels.

Figure 12. Two channels in cascade.

Figure 12 shows a channel with an input set X and an output set Y which is cascaded with a second channel. The input of the second channel is identified with Y and its output is denoted by Z. In this arrangement any particular z_k depends on the original input x_i only through y_j.

As variety is transmitted through cascaded channels from X to Y to Z, it seems plausible that the loss should increase. It can be shown that this is in fact the case, that

$$V(X/Z) \geq V(X/Y) \tag{15}$$

A consequence of formula (15) is the following:

$$T(X;Y) \geq T(X;Z) \tag{16}$$

These two formulas show that channels tend to "leak" variety. If however both channels are lossless and deterministic, i.e., noiseless, then the variety of X is replaced faithfully at Z.

To calculate the throughput variety for two channels in cascade we can use the following formula:

$$T(X;Y;Z) = T(X;Y) - T(X;Y/Z) \tag{17}$$

This formula says that the total throughout variety equals the throughput variety in the first channel minus any loss due to the second channel. We will call this loss due to the second channel 'secondary loss.' It will be represented by T(X;Y/Z), i.e., the throughput variety from X to Y, given Z. With perfect channels the value of this secondary loss will be 0.

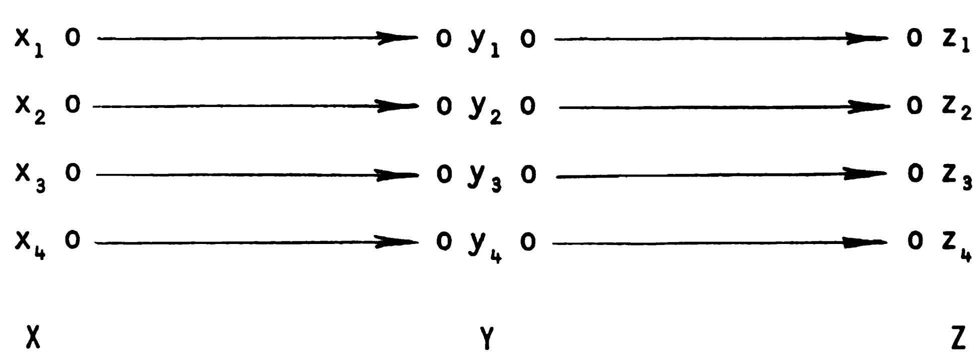

Figure 13. Two noiseless channels.

Formula (11) above gives us the value of T(X;Y). The following formula gives us the value of secondary loss.

$$T(X;Y/Z) = \sum_{x_i y_j z} P(x_i,y_j,z_k) \log_2 \frac{P(x_i,y_j/z_k)}{P(x_i/z_k)P(y_j/z_k)} \tag{18}$$

Note that with a noiseless channel as in Figure 13, the three probabilities in the fraction in (18), i.e., $P(x_i,y_j/z_k)$, $P(x_i/z_k)$, and $P(y_j/z_k)$ each equal 1, and thus the value of the fraction is 1. Since the $\log_2$ of 1 equals 0, the value T(X;Y/Z) is 0 in this case. There is thus no secondary loss and the throughput variety from X to Y is carried through to Z.

Summary

In this chapter we have shown that variety is related to the probability and hence disturbance of an event. A discrete memoryless source consisting of an ergodic Markov process generates states according to some probability distribution and the average disturbance was called the "variety" of the source. We then considered the form of a channel through which the variety from the source was transmitted to a receiver. In particular we established a measure of actual rate of variety transmission, i.e., throughput variety, as expressed by T(X;Y). Finally, the measurement of the throughput variety for two channels in cascade was examined.

CHAPTER FOUR

THE SELF-REGULATION MEASURE

Introduction

The 20th century has been characterized as the "Age of Automation." The automatic control of services formerly performed by human beings is becoming more and more prevalent, and no segment of society can escape the impact of these changes. A decrease in the role of unskilled workers and an increase in the role of skilled technicians is just one result. Automation, the automatic control of processes, has reached a high state of perfection.

Because of automation the world has plunged into a second industrial revolution. The first industrial revolution was based upon breakthroughs in power engineering, especially the steam engine and the many uses to which it was put. The second industrial revolution is based upon breakthroughs in control engineering, especially the computer and its many uses. During the Second World War, servomechanisms were developed to achieve automatic control and then computers were added to make complex instructions for automatic control possible. The shift in engineering was from an emphasis on increasing power to an emphasis on increasing control and communication. And thus "cybernetics," the science of control and communication was founded.[1]

But this shift in emphasis also has ramifications in many other areas. In particular, it marks a shift in viewpoint in many of the natural sciences.

> The late John von Neumann once pointed out that in the past science has dealt mainly with problems of energy, power, force, and motion. He predicted that in the future science would be much more concerned with problems of control, programming, information processing, communication, organization, and systems.[2]

Now while automation is a 20th century phenomenon on the technological scene, it has been prevalent on the biological scene for eons of time. Automatic control of growth and development, and automatic control of physiological processes are fundamental characteristics of living phenomena. The cybernetic point of view however was not used until recently in the analyses of these phenomena. It wasn't until man-made devices of automatic control were constructed that the concepts of cybernetics were brought to bear on biological research. And it is in the science of physiology especially that the cybernetic concepts are used as the fundamental concepts guiding research and interpretation.

The cybernetic point of view is the one used by contemporary physiologists and it is the context for the construction of our

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[1]Norbert Wiener, Cybernetics (Cambridge, Mass.: MIT Press, 1961), p. 11.

[2]Arthur W. Burks, "Von Neumann's Self-Reproducing Automata," in Essays on Cellular Automata, ed. by Arthur W. Burks (Urbana: University of Illinois Press, 1970), p. 3.

explicatum. In our discussion of explication in Chapter One, the construction of an explicatum was described as the second phase of an explication. It is this second phase which we now proceed to work out. Before we proceed however, the reader should be clearly aware of what we are attempting and what we are not attempting. A contrast of our explicatum for $function_1$ with Carnap's explicatum for $probability_1$ will point out clearly what we intend to do in this chapter.

The goal of our study does not have the same scope as Carnap's work on probability. In Logical Foundations of Probability, Carnap is attempting to construct an axiom set for inductive logic. He is attempting to arrive at a set of axioms from which, in a semi-formal way, the theorems of inductive logic could be derived. In other words, Carnap is attempting an axiomatization of inductive logic. In this chapter, however, we are not attempting an axiomatization of the science of physiology. Thus the scope of this chapter is not the same as Carnap's explication of 'probability.'

What this chapter does attempt is a formalization of one concept in physiology. A definition of 'function' is stated in terms of principles of the transmission of variety. Now Carnap also gives a formal definition for 'probability' as part of the development of his axiom set for inductive logic. In an analogous fashion, the concept of function here explicated could be used as the basis of an axiom set for physiology. An explication allows us to transform sentences about physiological functions into sentences which do not contain the term 'function,' but rather that contain terms referring to the transmission of variety.

A second difference between this explication and Carnap's explication lies in the fact that Carnap is explicating a logical concept whereas we are explicating an empirical concept.

A third difference is found in that Carnap used first order functional logic as the formal structure for his explicatum whereas we are using the theory of transmission of variety for the construction of the explicatum.

There are three major concepts related to the cybernetic point of view. These are the concepts of control, self-regulation, and self-organization. Our explicatum invokes the concept of self-regulation, and the other two concepts must be clearly distinguished from this concept.

'Control' describes management, with no specification as to how this management is performed. There are systems of control which are not self-regulating. Examples of this would be mechanical linkages such as those controlling gear-ratios in an automobile, or throttles controlling engine speed. The term 'regulation' is sometimes used synonymously with 'control.' The concept of control might be explicated by what we referred to earlier as the concept of function_2, or the mathematical concept of function: For each change in the independent variable there is a change in the dependent variable. This captures the concept of control but not the concept of self-regulation. Self-regulation does involve control as <u>part</u> of its meaning but it is a particular type of control, i.e., one which compensates for disturbances to produce a steady-state. Thus self-regulation is a special case of control.

Self-organization is another concept which must be clearly distinguished from self-regulation. A self-organizing system is one which changes its pattern of control, its physical structure, or its method of self-regulation over time so as to perform more efficiently. A self-regulating system, for example, might begin operating with a certain amount of efficiency but as it continued to operate it might automatically restructure its pattern of operation, say by changing its set point, and become more efficient as a self-regulator. This process of change of patterns of control is self-organization; it is analogous to the concept of learning. Other self-regulating systems are not self-organizing. The average home heating system has a self-regulating temperature but it is not self-organizing. After years of operation it still operates the same way. Thus, self-organization, while not incompatible with self-regulation, is not equivalent to it. Self-organization is viewed over a relatively longer time span and involves change in the pattern of control. This change in pattern of control can be seen as homeostatic or self-regulatory, i.e., as approximating closer and closer to a certain level of performance. Or it can be seen as not being self-regulatory. If over a period of time a machine re-adjusts its pattern of control so that its <u>rate</u> of production continually expands, then this machine would be self-organizing but not in a homeostatic fashion.

Computers have been designed and built that "learn" strategies as they play chess. This form of self-organization does not, however, maintain a steady-state, as in self-regulated systems. After each game the strategy of the chess machine changes; thus you have the output varying as the input varies. This is not the pattern of self-regulation.

Inadequacies of Previous Explications

In Chapter Two we discussed the choice of an explicandum for our explication of 'function.' There it was pointed out that while the concept of a self-regulated or goal-directed system was used as an explicatum by a few authors, the explicandum for which it was constructed was not the concept of function_1, but a much broader concept of purposive behavior, which included both function_1 and function_3. Now in this present section we would like to refer again to those authors who used goal-direction or self-regulation as their explicata, this time focusing upon the details of their explicata. In particular we would like to show that the explicata can be improved in at least two distinct ways to provide a better explicatum for self-regulated physiological processes. The fact that the models are limited to deterministic processes only, and that they provide only a qualitative or classificatory concept, both represent inadequacies which we hope to correct.

G. Sommerhof published his Analytical Biology in 1950 and the model proposed in that book has been the basis of all explications using the idea of goal-directedness that later philosophers of science have proposed. We would do well then to examine this influential explication.

Sommerhof introduces his model intuitively as follows. He gives instances of "adaptation," taking it in its broad sense to cover "the various forms of purposiveness found in nature."[3] He sees adaptation as an instance of the concept of "appropriateness." The appropriateness of some activity, i.e., of a response, he sees as related to three factors. These are the stimulus, the concomitant situation, and the goal. Thus if an anti-aircraft gun "perceives" a target (stimulus), the gun, determining its own position (concomitant situation) adjusts its direction (response) to bring it into alignment with the target (goal). This basic pattern of activity is called "directive correlation." Figure 14 represents this activity, where the stimulus or "coenetic variable" is represented by CVt_0, the response by Rt_1, the concomitant situations by Et_1, and the goal or "focal condition" by Gt_2.

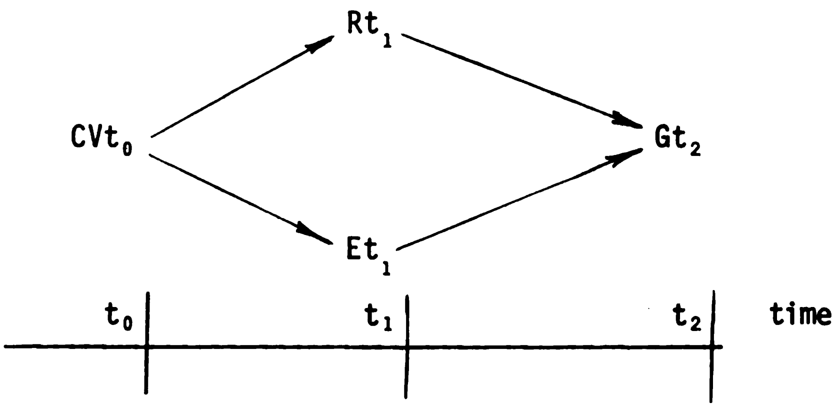

Figure 14. Directive correlation.

[3]G. Sommerhof, Analytical Biology (London: Oxford University Press, 1950), p. 54.

Somerhof defines "directive correlation" in this way:

> Any event or state of affairs Rt_1 occurring at a time t_1 is directively correlated to a given simultaneous event or state of affairs ET_1, in respect of the subsequent occurrence of an event or state of affairs Gt_2 if the physical system of which these are parts is objectively so conditioned that there exists an event or state of affairs CVt_0 such that
>
> (a) under the given circumstances any variation of CVt_0 within this set implies variation of both Rt_1 and Et_1;
>
> (b) any such pair of varied values of Rt_1, Et_1 (as well as the pair of their actual values) is a pair of corresponding members of two correlated sets of possible values $R't_1$, $R''t_1$, $R'''t_1$, . . . and $E't_1$, $E''t_1$, $E'''t_1$, . . . , which are such that under the circumstances all pairs of corresponding members, but no other pairs, cause the subsequent occurrence of Gt_2.[4]

To take a physiological example, if the environmental temperature increases (CVt_0) then the effect on the interior of the organism (Et_1) is compensated for by an increased perspiration rate (Rt_1) with the result that the interior temperature remains normal (Gt_2).

Ernest Nagel also uses the same approach as Sommerhof.[5] In The Structure of Science, Nagel defines a system S having three state variables, A_x, B_y, and C_z. Some sets of values of these variables are causally relevant to the production of a G-state (goal state). The system operates deterministically. Nagel qualifies the possible values of A_x, B_y, and C_z by stating that the range of values of these variables must be compatible with the known physical character of the parts

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[4] Ibid., pp. 25-26.

[5] Ernest Nagel, The Structure of Science (New York: Harcourt Brace & World, 1961), p. 411, n. 4, "The following discussion is heavily indebted to G. Sommerhof, Analytical Biology (London: Oxford University Press, 1950)."

associated with these variables. This restricted range of values he labels 'K_A,' 'K_B,' and 'K_C.' Now Nagel describes the operation of his "system" by saying that for every pair of instants, $\{t_n, t_{n+1}\}$ in some interval T, every "primary variation" in the system at t_n is followed by an "adaptive variation" at t_{n+1}. A "primary variation" is a state of the system which is not a G-state and an "adaptive variation" is a state of the system which is a G-state. Nagel, like Sommerhof, puts no restriction on what is or is not a G-state or "goal." Assuming each state variable A_x, B_y, C_z has possible values of 1, 2, and 3, for example, we can describe the operation of Nagel's system as shown in Figure 15. Let us assume that the system is in a G-state when all three state variables have the same value.

	A_x	B_y	C_z	
t_1	1	2	1	primary variation
t_2	1	1	1	adaptive variation
t_3	3	1	2	primary variation
t_4	2	2	2	adaptive variation
t_5	2	2	3	primary variation
t_6	2	2	2	adaptive variation

Figure 15. Adaptive variation.

Nagel then defines the next-state and next-output $functions_2$ of his system S in terms of classes. "For each value in K_A' there is a unique pair of values, one member of the pair belonging to K_B' and the other to K_C,' such that for those values S continues to be in a G-state at time t_1."[6] In our above example, for $K_A' = \{1, 2, 3\}$ we have the corresponding sets $K_B' = \{1, 2, 3\}$ and $K_C' = \{1, 2, 3\}$. The set of G-states of the system are $\{1, 1, 1\}$, $\{2, 2, 2\}$, and $\{3, 3, 3\}$.

The first point to notice is that both Somerhof and Nagel deal with deterministic control systems. Now in the realm of living organism and their systems we do not always find this to be the case. The channels of transmission in living systems are not made of wires and switches so that closing a switch at point A always closes the switch at B. Rather, much of the variety is transmitted via hormonal pathways in the bloodstream. This means that although there is a high probability that a disturbance signal will reach its target, there is no deterministic connection. Even neural pathways have certain impediments and qualifications which give the transmission of variety over them a probabilistic character.

The type of behavior pattern described by the deterministic models of Sommerhof and Nagel is too rigid or automatic to adquately reflect the actual behavior of physiological processes, which do not operate with quite the precision of deterministic models. The models of Sommerhof and Nagel apply only to systems with 100% efficiency. This is an over-simplified treatment and the measure of self-regulation we propose in this chapter is designed to more accurately capture the

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[6]<u>Ibid</u>., p. 411.

behavior of physiological systems by its use of probability functions instead of deterministic functions.

This probabilistic character of physiological systems is the reason for the choice of the theory of variety as the formal system in terms of which we will formalize the concept of self-regulation. The probabilistic approach of variety theory is appropriate for handling physiological processes, and deterministic processes, e.g., machines, can also be handled, by assuming a conditional probability of 1.0 in the channels.

The second inadequacy of the models is that they provide only a classificatory, i.e., qualitative, explicatum. On the basis of their models we can only assert that a system is or is not an example of directive correlation. There is no way to decide <u>how much</u> directive correlation is found in a system. As we noted in Chapter One, where it is possible, a quantitative explicatum provides a more precise concept than a comparative or classificatory one. Since the ultimate goal of an explication should be the construction of as precise a concept as possible, the quantitative concept should be constructed where it can be done. On the models of Sommerhof and Nagel, a system which is self-regulatory in the face of a disturbance range of only two values is considered the same as one that is self-regulated in the face of a disturbance range of 25 values. Nagel does add the ad hoc qualification that there must be more than one value for the range of disturbance, thereby ruling out the trivial case where the system is self-regulated in the face of no disturbance.

Nagel also indicates the direction which one could take to formulate a quantitative concept of directive organization involving his model.

> The more inclusive the range K_A' that is associated with such compensatory changes, the more is the persistence of G independent of variations in the state of S. Accordingly, on the assumption that it is possible to specify a measure for the range K_A', the "degree of directive organization" of S with respect to variations in the state parameter 'A' could be defined as the measure of this range.[7]

The self-regulation measure proposed in this chapter is an attempt to follow up the suggestion of Nagel, although in a somewhat different manner. One of the drawbacks of Nagel's proposed quantitative concept is that it would apply only to systems with 100% efficiency. Physiological systems do not possess this accuracy and thus any model must be more complex.

A Measure of Self-Regulation

The explicandum which we are trying to explicate is described as the concept of $function_1$. This concept was defined by four conditions, and it would be wise to review these conditions so that the reader will see the relevance of our formalized construction of an explicatum. Something is a $function_1$ if it meets the following conditions:

1. The $function_1$ is a process, i.e., a spatio-temporal structure.
2. The process can be described in terms of "black boxes," i.e.,

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[7] *Ibid.*, p. 417.

systems, each consisting of an input, output, and transfer function.

3. The output is relatively stable, i.e., relative to the input.
4. A mechanism of active compensation, directed by the input, is used to control the relative stability of the output.

Claude Bernard's conception failed to capture the fourth condition clearly, although it satisfied 1, 2, and 3. His viewpoint stressed the steady-state but did not specify the details of the mechanism of active compensation.

It is important to note that Condition 4 describes an essential part of the concept of $function_1$. There are two ways in which a steady-state can be achieved. One is by active self-regulation, the other is by passive self-regulation. This latter should more properly be termed "pseudo-self-regulation."

Systems of passive or pseudo-self-regulation are those in which the variety in the input is blocked so that the output variety is reduced or eliminated. See Figure 16.

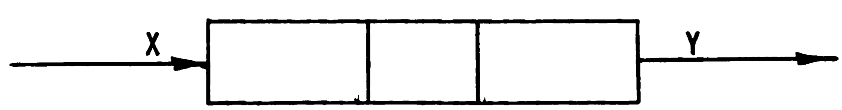

Figure 16. Pseudo-self-regulation.

In these systems there is some form of "insulation" between X and Y. Common examples of this form of pseudo-self-regulation can be found in the thermos flask, the bark of a tree, the shell of a turtle, etc. The fourth condition of our explicandum rules out such cases by requiring that the steady-state be achieved through <u>active</u> self-regulation.

The active self-regulation concept was given formal rigor with the development of the idea of negative feedback. In 1927 a "negative feedback" amplifier was invented by H. S. Black.[8] Soon the mechanism of negative feedback was being employed in a variety of applications, and the concept began to enter into the analysis of biological systems. Figure 17 gives the general pattern of a negative feedback circuit.

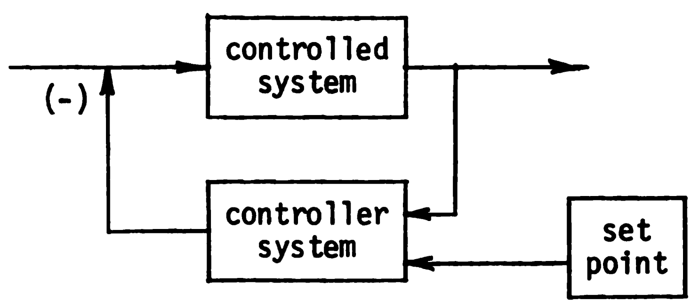

Figure 17. Negative feedback system.

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[8]J. R. Pierce, <u>Symbols, Signals and Noise</u> (New York: Harper & Bros., 1961), p. 216.

Some characteristics of this type of circuit must be noted. First of all, the energy for the regulation does not come from the disturbance, rather it comes from the controller system. Secondly, in view of the previous point, it is the variety, i.e., the variational aspect of the input medium, not its chemical or physical aspect that is utilized. The controller system views the medium as a <u>message</u>. Norbert Wiener emphasized this point when he said:

> . . . it had already become clear to Mr. Bigelow and myself that the problems of control engineering and of communication engineering were inseparable, and that they centered not around the technique of electrical engineering but around the much more fundamental notion of the message, whether this should be transmitted by electrical, mechanical, or nervous means. The message is a discrete or continuous sequence of measurable events distributed in time--recisely what is called a time series by the statisticians.[9]

Now let us set up a cybernetic model, which we will call a "physiosystem," for a physiological, i.e., self-regulated, process. A "physiosystem" is a network of three channels and is defined as the set

$$\{D, C, P, P(p_j/d_i), P(c_k/d_i), P(p_j/c_k)\}$$

where D is the set of input events $\{d_i\}$ and $i = 1,2,...q$;

P is the set of pool events $\{p_j\}$ and $j = 1,2,...r$;

C is the set of control events $\{c_k\}$ and $k = 1,2,1...s$;

$P(p_j/d_i)$ is the transition probability from d_i to p_j;

$P(c_k/d_i)$ is the transition probability from d_i to c_k;

$P(p_j/c_k)$ is the transition probability from c_k to p_j.

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[9]Wiener, <u>op. cit</u>., pp. 8-9.

The symbol 'P' when attached to an argument in parentheses, e.g., '$P(d_i)$' or '$P(c_k/d_i)$' will refer to probability. All other uses of 'P' will refer to the pool of material to be regulated.

The elements in our physiosystem set define for us three channels connected as shown in Figure 18.

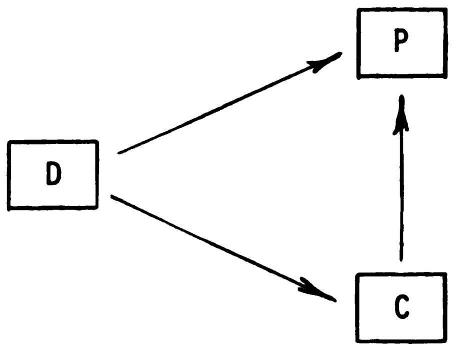


Figure 18. A physiosystem.

The overall effect of self-regulation is that some pool, P, of material, e.g., heat, sodium ions, water, etc. is kept in a steady-state relative to an influx of disturbances, D, by a mechanism of active compensation, C. The physiologist Walter B. Cannon puts it this way: "If a state remains steady it does so because any tendency towards change is automatically met by increased effectiveness of the factor or factors which resist the change."[10] In our physiosystem we have the channels $D \rightarrow C$ and $C \rightarrow P$ in cascade, i.e., in series, providing the negative feedback

[10]Walter B. Cannon, The Wisdom of the Body (New York: W. W. Norton Co., 1939), p. 299.

which controls the variety transmitted to the pool via $D \rightarrow P$. To the degree then that the channel $D \rightarrow C \rightarrow P$ blocks the variety going from $D \rightarrow P$, to that degree the physiosystem is an effective or efficient self-regulating system.

In actual operation of living systems we have the following situation. With respect to some substance, variations, D, occur to the living system. If no control channel, i.e., compensation, occurred this variety would be transmitted to the "milieu interieur" or pool, P, of the system. The amount of variety actually transmitted from D to P would thus be a measure of this. The control channel $D \rightarrow C \rightarrow P$ however blocks this original disturbance and if the self-regulation is 100% effective, then the variety reaching P from D is cancelled and P shows no change; it manifests a steady-state. On the basis of this analysis we define self-regulatory efficiency of the physiosystem.

$$eff_{SR} = \left(1 - \frac{T(D;C;P)}{T(D;P)}\right) \times 100 \qquad (19)$$

where $T(D;C;P)$ is the throughput variety of channels $D \rightarrow C$ and $C \rightarrow P$ in cascade; and

$T(D;P)$ is the throughput variety without the control channel in operation.

The calculation of the throughput variety for two channels in cascade was discussed in the previous chapter (pages 151-153), and especially see equations (17) and (18). The throughput variety of a single channel was discussed on pages 142-150 of the previous chapter; see especially equation (12).

With a perfect self-regulator then, the throughput variety from D to C to P will be 0 and thus the self-regulatory efficiency will be

$$eff_{SR} = \left(1 - \frac{T(D;C;P)}{T(D;P)}\right) \times 100 \qquad (19)$$

$$= \left(1 - \frac{0}{T(D;P)}\right) \times 100$$

$$= 1 \times 100$$

$$= 100\%$$

Now with an imperfect self-regulator, let us say that only three-fourths of the disturbance is blocked, i.e.,

$$\frac{T(D;C;P)}{T(D;P)} = \frac{1}{4} .$$

This means that 1/4 of the input disturbance "leaked through" the control channel. The efficiency would thus be given as

$$eff_{SR} = \left(1 - \frac{T(D;C;P)}{T(D;P)}\right) \times 100 \qquad (19)$$

$$= \left(1 - \frac{1}{4}\right) \times 100$$

$$= \frac{3}{4} \times 100$$

$$= 75\%$$

With a self-regulator having 0% efficiency we would have

$$\frac{T(D;C;P)}{T(D;P)} = 1.$$

This means that the amount of variety going through to P with the control channel in effect is equal to the amount of variety going through to P without the control channel. Thus we have

$$\begin{aligned} \mathrm{eff}_{SR} &= 1 - \frac{T(D;C;P)}{T(D;P)} \times 100 \qquad (19) \\ &= (1 - 1) \times 100 \\ &= 0\% \end{aligned}$$

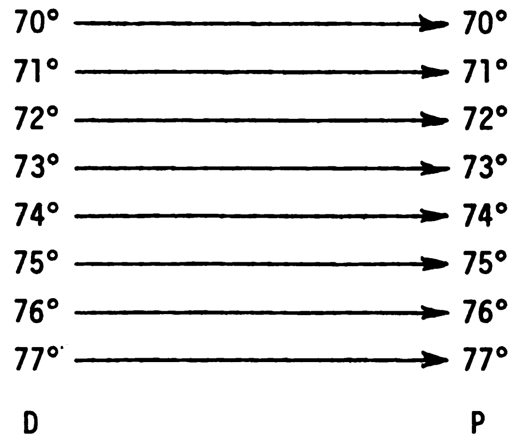
Now let us examine some specific cases, i.e., examples of probability values in a physiosystem and calculate the self-regulatory efficiency of these physiosystems. We will invoke the measures of variety that were discussed in Chapter Three, especially the measures of throughput variety. The reader should review Chapter Three if he does not remember these measures clearly.

Let us assume for our first case a physiosystem which works on the basis of temperature variations in degrees Fahrenheit. Let us also assume that this is a perfect self-regulator, i.e., its efficiency = 100%. Figure 19 describes this physiosystem.

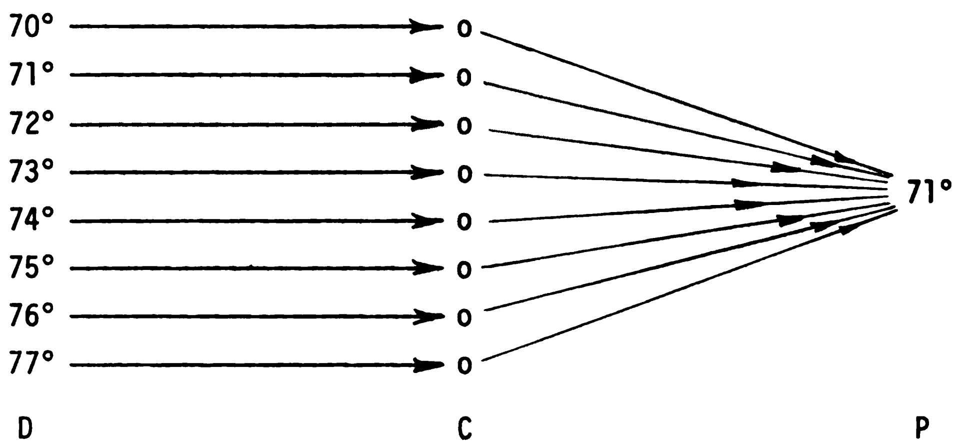
We will assume the simple case for the moment in which the initial probabilities are equal. We will also assume that the transition probabilities are as follows:

for all i, $P(p_i/d_i) = P(c_i/d_i) = P(p_i/c_i) = 1$;

for all other values the probabilities equal 0.



(a) throughput variety with no control



(b) throughput variety with control

Figure 19. Perfect self-regulation.

Now the throughput variety for D→P without the controller would be calculated as

$$T(D;P) = V(P) - V(P/D) \tag{20}$$

Again the reader is referred to the previous chapter for a discussion of this quantity, especially pages 142-150. The variety in P would be found by

$$\begin{aligned} V(P) &= \sum_{P} P(p_j) \log_2 \frac{1}{P(p_j)} \qquad (21) \\ &= \sum_{P} \frac{1}{8} \log_2 \frac{1}{1/8} \\ &= 1 \times 3 \\ &= 3 \text{ bits} \end{aligned}$$

The noise in the channel would be found by

$$\begin{aligned} V(P/D) &= \sum_{D} P(d_i) \sum_{P} P(p_j/d_i) \log_2 \frac{1}{P(p_j/d_i)} \qquad (22) \\ &= 0 \end{aligned}$$

Thus the throughput variety for D→P if there were no self-regulation, is

$$\begin{aligned} T(D;P) &= V(P) - V(P/D) \qquad (20) \\ &= 3 - 0 \\ &= 3 \text{ bits} \end{aligned}$$

The throughput variety with the self-regulator operating is calculated from the formula for two channels in cascade:

$$T(D;C;P) = T(D;C) - T(D;C/P) \tag{23}$$

As can be seen from Figure 19 (b), the throughput variety T(D;C) could be calculated as

$$T(D;C) = V(C) - V(C/D) \tag{24}$$
$$= 3 - 0$$
$$= 3 \text{ bits}$$

The total throughput variety of the two channels in cascade is equal to the throughput variety of D→C minus the secondary loss, T(D;C/P). This secondary loss can be calculated as

$$T(D;C/P) = \sum_{D,C,P} P(d_i,c_k,p_j) \log_2 \frac{P(d_i,c_k/p_j)}{P(d_i/p_j)\; P(c_k/p_j)} \tag{25}$$
$$= \sum_{D,C,P} P(d_i,c_k,p_j) \log_2 \frac{1/8}{1/8 \times 1/8}$$
$$= (64 \times 1/64) \log_2 8$$
$$= 1 \times 3$$
$$= 3 \text{ bits}$$

The throughput variety of the two channels then is

$$T(D;C;P) = T(D;C) - T(D;C/P) \tag{23}$$
$$= 3 - 3$$
$$= 0 \text{ bits}$$

Since T(D;P) as we saw earlier is 3 bits, the efficiency of the physiosystem is given as

$$\text{eff}_{SR} = \left(1 - \frac{T(D;C;P)}{T(D;P)}\right) \times 100 \tag{19}$$
$$= \left(1 - \frac{0}{3}\right) \times 100$$
$$= 1 \times 100$$
$$= 100\%$$

Figure 19 then describes what we could call a perfect self-regulator. All the possible variety is blocked to yield a stable pool of substance.

At this point we must bring out the fact that the measure of efficiency is an estimation of the true efficiency of the physio-system. This estimation approaches the actual efficiency as the sensitivity of the channel, i.e., the size of the units used, is made finer and finer. While the measure of variety V(X) is relative to the units used, i.e., the smaller, and thus more numerous, the units, the greater is the variety. The throughput variety, T(X;Y) is not relative to the size of the units. As one increases the sensitivity, i.e., fineness of the units, one increases the input variety, V(X), but one will also increase the noise. The amount of this increase of noise will depend upon the actual structure of the channel. Thus the throughput variety, measured as

$$T(X;Y) = V(X) - V(X/Y) \tag{14}$$

will not increase proportionately, but rather, while V(X) will increase, so will V(X/Y) and thus T(X;Y) will stabilize and converge on some limiting value, assuming that there is such a value, i.e., a capcity of the channel.[11]

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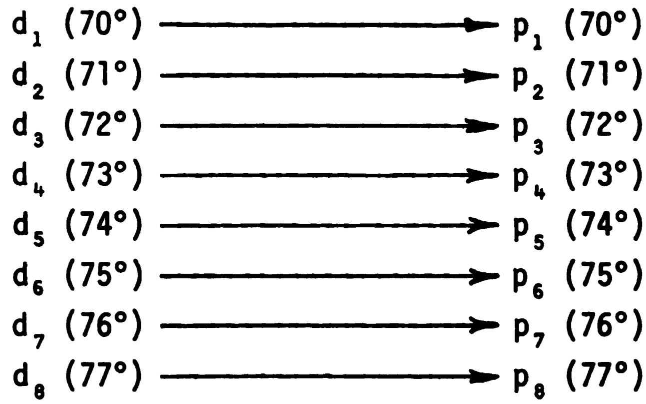
[11]Those instances of physiological systems involving continuously varying states are not quite as straightforward as those involving discrete states. It does not yet appear clear whether a certain relativity in the channel measurements may or may not be ineradicable.

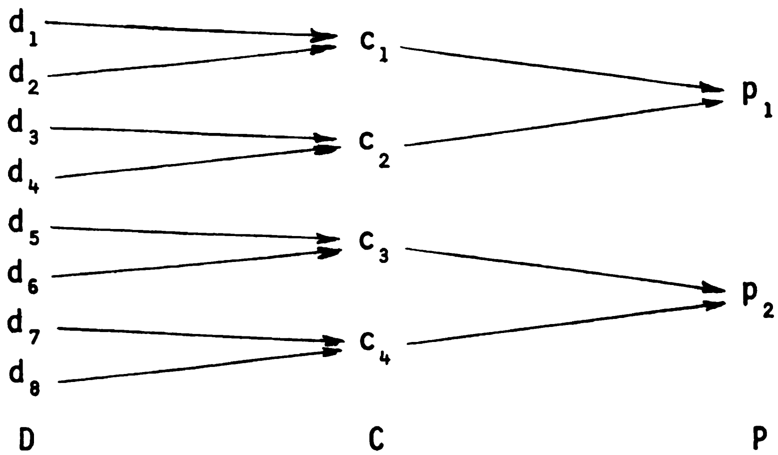
Since the efficiency measure is the ratio of throughput variety measures, its value approaches some limit.

One might also note that the efficiency measure, $\frac{T(D;C;P)}{T(D;P)}$, is relative to the D→P channel, i.e., the channel without the controller. The size of T(D;P), the dencminator in our efficiency measure, will influence the amount of efficiency. This aspect of our explicatum shows quite clearly how the notion of self-regulation is relative to the size of the disturbance. When speaking of a system as self-regulated, one means that it is self regulated with respect to some disturbance. The range of disturbance for which the physiosystem compensates is an essential part of its meaning. Self-regulation is like the concept of probability or the concept of freedom in that it is a relative concept.

With these two points in mind let us refer for our second case to self-regulation of tempature again but in this case we will assume first that the input disturbances, D, are not equiprobable, and also that the control channel does not block all of the disturbance variety. Figure 20 describes such an imperfect regulator with non-equiprobable input.



(a) the channel without the self-regulator operationg



(b) the channels D→C→P with some self-regulation effective

<u>D</u>		<u>C</u>		<u>P</u>	
d_1:	1/16	c_1:	1/4	p_1:	1/2
d_2:	1/16	c_2:	1/4	p_2:	1/2
d_3:	1/16	c_3:	1/4		
d_4:	4/16	c_4:	1/4		
d_5:	4/16				
d_6:	3/16				
d_7:	1/16				
d_8:	1/16				

(c) probability distributions

Figure 20. Imperfect self-regulation.

Now assuming the transition probabilities are all equal to 1, what is the efficiency of this physiosystem?

The variety in the pool, P, without self-regulation is given as

$$V(P) = \sum_{P} P(p_j) \log_2 \frac{1}{P(p_j)} \tag{21}$$

$$= 2.7 \text{ bits}$$

Since the transition probabilities are all equal to 1, there would be no noise, i.e., V(P/D) = 0. The throughput variety of D→P without the controller would thus be

$$T(D;P) = V(P) - V(P/D) \tag{20}$$

$$= 2.7 - 0$$

$$= 2.7 \text{ bits}$$

Now to calculate the throughput variety from D to C to P we need to know T(D;C) and T(D;C/P). We can calculate the throughput variety from D to C as either the output variety minus the noise, as in (2) or as the input variety minus the loss. We will use the latter method.

$$T(D;C) = V(D) - V(D/C) \tag{25}$$

Now the loss V(D/C) is given as

$$V(D/C) = \sum_{C} P(c_k) \sum_{D} P(d_i/c_k) \log_2 \frac{1}{P(d_i/c_k)} \tag{26}$$

$$= 4 \times 1/4 \times 1$$

$$= 1 \text{ bit}$$

Since V(D) = 2.7, then we have

$$T(D;C) = V(D) - V(D/C) \tag{25}$$
$$= 2.7 - 1$$
$$= 1.7 \text{ bits}$$

The secondary loss, T(D;C/P) is calculated as follows:

$$T(D;C/P) = \sum_{D,C,P} P(d_i,c_k,p_j) \log_2 \frac{P(d_i,c_k/p_j)}{P(d_i/p_j)\, P(c_k/p_j)} \tag{25}$$
$$= 1 \times \log_2 \frac{1/4}{1/4 \times 1/2}$$
$$= 1 \times \log_2 2$$
$$= 1 \text{ bit}$$

The throughput variety of the two channels in cascade is thus given by

$$T(D;C;P) = T(D;C) - T(D;C/P) \tag{23}$$
$$= 1.7 - 1$$
$$= 0.7 \text{ bits}$$

The efficiency of this physiosystem can now be calculated as

$$eff_{SR} = \left(1 - \frac{T(D;C;P)}{T(D;P)}\right) \times 100 \tag{19}$$
$$= \left(1 - \frac{0.7}{2.7}\right) \times 100$$
$$= (1 - 0.26) \times 100$$
$$= 74\%$$

Thus the decrease in efficiency of the self-regulation is evident.

One other aspect of the self-regulation measure should be emphasized, namely, how the pseudo or passive self-regulation aspect is treated. In living systems there is sometimes a certain amount of insulation between the disturbance and the pool of substance. How does this affect our measure? The measure takes account of this by using throughput variety measures for the channels. The effect of insulation is measured as the loss, i.e., V(D/P). If the channel D→P is insulated so that a smaller amount of disturbance reaches P, then this insulation also occurs in the D→C→P channel; but this reduced variety reaching C will be enough to balance the reduced amount reaching P directly. In other words the insulation has an equal effect on both the D→P and the D→C→P channels and thus does not change the efficiency. The efficiency measure gives us the amount of control of variety that has passed through the insulation.

The case where the insulation is perfect, i.e., perfect pseudo-self-regulation, will be discussed after we complete the construction of our self-regulation measure.

One consequence of our efficiency measure is that if we consider two different physiosystems, one compensating for a variety of say 3 bits and the other for a variety, say of 6 bits, then both may still have the same efficiency. If both have control parts which compensate for all of the input variety, D, then both will have an eff_{SR} of 100%. It seems however that the physiosystem which self-regulates for 6 bits of input is a "better" self-regulator or has more self-regulatory capability than the one whose input variety is only 3 bits. This is what Nagel had in mind, too, in his suggestion of an approach toward developing a quantitative concept of goal-directed systems. But actually it is not the amount of input variety which may distinguish physiosystems, but rather the amount of control variety in response to that input variety. In our example above the physiosystem which efficiently compensated for 6 bits of variety is a better self-regulator because in order to so compensate, its capacity of control was greater. In other words it has 6 bits of control as compared to 3 bits for the other system.

To complete our explicatum then, of self-regulation, we must add to our efficiency measure a measure of amount of control. This can be measured by the throughput variety from D to C, i.e., T(D;C).

The amount of self-regulation, S, of a physiosystem can then be obtained by multiplying the efficiency of that system by the amount of variety in the input control channel, i.e., the channel from the disturbance to the controller. Thus we arrive at

$$S(D;C;P) = \left(1 - \frac{T(D;C;P)}{T(D;P)}\right) \times T(D;C) \tag{27}$$

The physiosystem described earlier in Figure 19 would have an amount of self-regulation, S, given as

$$\begin{aligned} S(D;C;P) &= \left(1 - \frac{T(D;C;P)}{T(D;P)}\right) \times T(D;C) \qquad (27) \\ &= 1.00 \times 3 \\ &= 3 \text{ bits} \end{aligned}$$

For the physiosystem in Figure 17, we would have

$$S(D;C;P) = (1 - \frac{T(D;C;P)}{T(D;P)}) \times T(D;C) \tag{27}$$
$$= 0.74 \times 1.7$$
$$= 1.258 \text{ bits}$$

Let us return now to the example of perfect pseudo-self-regulation, i.e., a perfect thermos bottle. Here we see that if one measures the throughput variety T(D;P) between the interior and exterior without the vacuum as insulation in the bottle, and then measures the throughput variety T(D;C;P) with the vacuum present, then, assuming T(D;C;P) = 0, we have $\frac{0}{T(D;P)}$, there is a perfect blockage of variety, and the efficiency would be

$$eff_{SR} = (1 - \frac{T(D;C;P)}{T(D;P)}) \times 100 \tag{19}$$
$$= (1 - 0) \times 100$$
$$= 100\%$$

This gives us the efficiency only.[12] When combining this with T(D;C) to obtain the amount of self-regulation, we see that T(D;C) = 0 and thus we have

$$S(D;C;P) = (1 - \frac{T(D;C;P)}{T(D;P)}) \times T(D;C) \tag{27}$$
$$= 1.00 \times 0$$
$$= 0$$

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[12]If one considered the channel D→P to be from the outside to the inside of a normal thermos bottle, then the value of this throughput variety would be 0 and T(D;C;P)/T(D;P) would equal 0/0 and thus the efficiency would be undefined in this case due to the 0 in the denominator. This seems intuitively plausible, since it makes no sense to speak of the amount of control per disturbance received when no disturbance is received, i.e., if T(D;P) equals 0.

The amount of self-regulation is 0 because the amount of control variety T(D;C) is 0. The "output' side of the insulating vacuum does not change and there is no throughput variety from D to C. The channel D→C→P is represented for such a case in Figure 21.

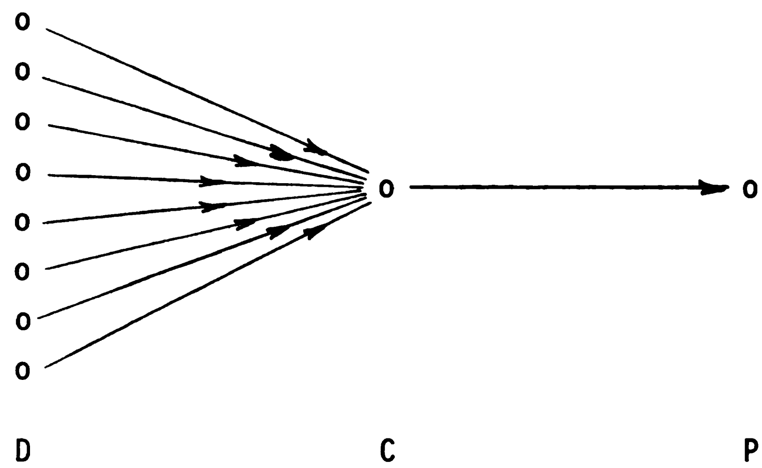

Figure 21. Insulated channel.

As can be seen, in a perfectly insulated thermos bottle, there is no variety in C's values and thus the throughput variety in D→C is 0.

Our measure, S, of self-regulation, uses our physiosystem model as its basis, i.e., the physiosystem as we have defined it is a general model which provides a quantitative concept of self-regulation. Other physiologists have constructed general models of self-regulating systems which are similar to ours except for the lack of a measure of amount of self-regulation. John R. Brobeck, for example, in his article "Exchange

Control, and Regulation" describes a model similar to our physiosystem.[13] The difference between control and regulation with Brobeck is what we have characterized as the difference between control and self-regulation. Thus Brobeck uses 'regulation' where we more correctly speak of self-regulation. That this is what he means by 'regulation' can be seen when he defines it as "the preservation of a relatively constant value by means of physiological mechanisms which include a specialized detector for the value or some function of it."[14] Control is not identical with regulation, rather "Controls are required to achieve regulation."[15]

Our physiosystem then is analogous to what Brobeck calls a "regulating system." He lists five essential conditions of a regulating (i.e., self-regulating) system:

1. an input, gain, intake
2. an output, loss, expenditure
3. a content
4. a mechanism for detecting content and/or changes in content
5. mechanisms for controlling intake and output, respectively.

Figure 22 describes such a system.

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[13]John R. Brobeck, "Exchange, Control, and Regulation," in Physiological Controls and Regulations, ed. by William S. Yamamato and John R. Brobeck (Philadelphia: W. B. Saunders, 1965),

[14]*Ibid*., p. 5.

[15]*Ibid*.

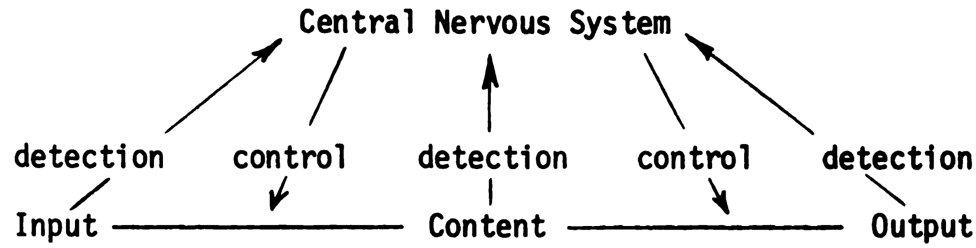

Figure 22. A regulatory model.

Comparing Brobeck's model with our physiosystem we have, corresponding to his input, output, and content, the disturbance D, the control C, and the pool P. The output in Brobeck's model describes the release of the excess substance. Since the amount released is determined by the controller, the variations in the controller are reflected in the variations in the output, and vice-versa. Also in the diagram, Brobeck has indicated that there is a controller, C, in the form of the Central Nervous System. The last two of Brobeck's conditions are given by our channels $D \to C$ and $C \to P$, respectively.

The channel $D \to P$ is found in our physiosystem but not in Brobeck's model because our physiosystem attempts to measure the amount of self-regulation and so we need a normalizing standard of how the system acts without any self-regulation. Since Brobeck does not measure the <u>amount</u> of self-regulation, he does not use this.

Thus we can see that the physiosystem upon which our measure of self-regulation is based, is in fact an accurate model for any physiological system.

The Adequacy of the Explicatum

In the first chapter we described three criteria of adequacy for any explicatum. These were relevance, preciseness, and simplicity. Let us see how our explicatum, amount of self-regulation, meets these criteria.

The explicatum should be relevant to the explicandum. As we stated in the first chapter, this means that there is an extensional equivalence of explicandum and explicatum in all cases where the object is clearly in or not in the explicandum class, and in those cases where it is not clear if some object is in the explicandum class, then membership in the explicatum class decides whether that object is in the explicandum class or not.

Now philosophers have sometimes debated whether the concept of function applies to artificial systems, i.e., machines, as well as to living systems. On our analysis, artificial systems, e.g., thermostat-controlled heating systems, and other similar devices can be said to function$_1$ in an identical manner as living systems. Consider a thermostatically-controlled incubator designed to remain at a certain temperature. D would be a set of input disturbances, P would be the interior of the incubator and C would be the control mechanism. One example of a control mechanism is a capsule in the interior which swells as the temperature rises. The capsule is constructed within the fuel line feeding the incubator's heat source, and as the capsule swells it decreases the amount of fuel and thus the heat, going to the incubator. If the temperature goes below the desired level, the capsule shrinks, allowing more fuel to reach the heating unit and thus increases the temperature. Figure 23 shows the process.

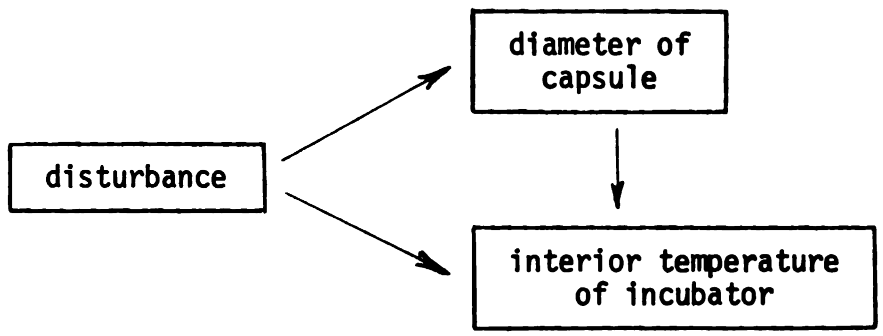

Figure 23. Self-regulating incubator.

Another group of examples for which it is not clear as to whether they are instances of self-regulatory functions is that made up of examples of chemical equilibrium. Can reactions in the test tube which reach equilibrium be considered "self-regulating?" Our explicatum clarifies and answers this question.

Chemical systems in general are of two types: closed systems and open systems. Now both types attain a form of "equilibrium" but the equilibrium is not really the same in both cases. A closed system is a system isolated from its environment, the quantities of substance are fixed. An open system is a system whose substances are in exchange with its environment. An example of a closed system would be a reversible ionic reaction in an isolated container. The following equation describes such a reaction.

$$AgCl \rightleftharpoons Ag^+ + Cl^- \tag{28}$$

An example of an open system would be the same reaction, except that silver ions are continuously added from the environment. Now when silver ions are added to the right side of the equation (28), the equilibrium position shifts to the left, more AgCl is produced and the system compensates in this way for the addition of the silver ions. This is stated by Le Chatelier's principle, i.e., if the conditions of a system in equilibrium are changed, the equilibrium will shift in such a way as to tend to counteract the change. Likewise, if one were to remove AgCl, the equilibrium position would also shift to the left. If one were to add AgCl or remove Ag^+ or Cl^-, the equilibrium position would shift to the right. The principle of Le Chatelier is used to advantage in many industrial processes. For example, the commercial production of ammonia is based on the reaction

$$N_2 + 3H_2 \rightleftharpoons 2NH_3. \tag{29}$$

Now according to the law of mass action, the proportion of NH_3 to N_2 and H_2 is constant, i.e.,

$$K = \frac{[NH_3]^2}{[N_2]\,[H_2]^3} \tag{30}$$

The addition of either N_2 or H_2 to the reaction would increase the denominator in the above formula, thus tending to decrease the value of K. The system reacts however by converting more N_2 and H_2 to NH_3 in quantities sufficient to maintain the value of K. Also, the removal of

NH_3 from the system tends to decrease the value of K, the system again reacting by forming more HN_3 to maintain the value of K constant. It is thus possible to increase the production of NH_3 by maintaining large amounts of either N_2 or H_2 in the reaction chamber, or by removing NH_3 from the reaction chamber.[16]

It must be realized that open systems do not "violate" the principle of entropy. If one considers an open system in a wider context, i.e., involving the expenditure of energy needed to add or remove the material from the reaction chamber, then overall, considering this wider context, the entropy is decreasing as in a closed system.

Ludwig von Bertalanffy, in his General System Theory indicates how life processes are processes consisting of such open chemical systems. "For open chemical systems are indeed realized in nature in the form of living organisms, maintaining themselves in a continuous exchange of their components."[17] The equilibrium tendencies given by Le Chatelier's principle thus for von Bertalanffy "indicate the general physical foundations of that essential characteristic of life, self-regulation of metabolism and maintenance in change of components."[18]

What is being proposed here is that in chemical equilibria of closed systems, the entropy tends to increase, i.e., energy runs downhill. In open chemical systems and in physiological equilibrium the

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[16]Paul R. Frey, College Chemistry (Englewood Cliffs, N.J.: Prentice-Hall, 1958), p. 312.

[17]Ludwig von Bertalanffy, General System Theory (New York: George Braziller, 1968), p. 123.

[18]Ibid., p. 124.

entropy tends to decrease, i.e., the variety or "randomness" becomes small. This occurs, of course, at the cost of energy to maintain the parts of the physiological system, but this aspect does not enter into the pattern of self-regulation.

The difference between open chemical systems such as that used for producing ammonia, as described in equation (29), and physiological systems is simply a matter of different types of structural parts. The former utilizes man-made parts such as metal pumps whereas the latter uses "organic" parts. Essentially, though, they are both chemical systems.

There are many ways to show the usefulness of the measure of self-regulation. One physiologist, E. F. Adolph, has done some preliminary work in his investigation of how the ability to self-regulate improves as an organism develops from embryo to adult.[19] Adolph's determination of self-regulation rests upon a large number of varied tests such as increased complexity of mechanism, wider range of stresses regulated by the organism, etc. He nowhere in his work propounds a precise general concept of self-regulation. The general conclusion of his work is that

> In general, physiological regulations shift from early stereotypy to later plasticity as more extrinsic influences become effective and as adaptations to environment materialize. They also shift from independence to integration, or from isolation to grouping, as special regulations increase in number.[20]

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[19]E. F. Adolph, Origins of Physiological Regulations (New York: Academic Press, 1968).

[20]Ibid., p. 127.

It is clear that a general study such as Adolph proposes could benefit immensely from a precise general concept of self-regulation such as our measure of amount of self-regulation, S, provides.

A more accurate method of comparing species on a physiological basis is also facilitated by our measure. In an earlier work on self-regulation, Adolph asserted that "by the degree of constancy I can characterize diverse manifestations in one species, can compare similar manifestations in diverse species, ..."[21] Another physiologist, C. Ladd Prosser, has studied self-regulatory patterns in various animal species in an attempt to represent "physiological races," i.e., races or groups based upon degrees of function_1.[22] A quantitative concept of self-regulation would be of some help in providing a precise method for ordering species according to their self-regulatory capability.

One final point can be made relating to the relevance of the explicatum proposed in this chapter. Physiologists in the 20th century have more and more come to see the prevalence of self-regulated processes in the biological world. Adolph puts it this way: "Arrangements for self-governments have been found in all vital activities that have been suitably examined. Such intrinsic controls cannot be wholly separated from processes themselves."[23] The universality of this type of process is a reason why it can be claimed to constitute the

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[21]E. F. Adolph, Physiological Regulations (Lancaster, Pa.: Jaques Cattell Press, 1943), p. 2.

[22]C. Ladd Prosser, "Physiological Variation in Animals," Biological Reviews, XXX (1955), 229-62.

[23]E.F. Adolph, "Early Concepts of Physiological Regulation," Physiological Review, XLI (1961), 737.

fundamental concept of physiology. Speaking about the term 'homeostasis,' one physiologist has said that "the cluster of ideas which center about this word has a strong claim to being one of the few truly general and basic principles of physiology."[24]

Thus the fundamental nature of the concept of self-regulation is evident. Now J. H. Woodger, the well-known philosopher of biology, has emphasized that "the need for a critical review of its principal difficulties and fundamental notions is perhaps greater in biology than in any other science."[25] By our analysis of the concept of function in this dissertation we hope to have made some progress in fulfilling that need.

The relevance of our explicatum to the traditional philosophical problems attached to the concept of function has been anticipated somewhat in Chapter Two, where we discussed the analysis of 'function' by other philosophers. The explicatum discussed in this chapter results, moreover, in a correct interpretation of the so-called "future orientation" or "teleological" aspect of living processes. Because our explicatum provides a measure of the <u>capacity</u> of the physiosystem to block disturbances, we are specifying not any particular behavior of the system, but the <u>potential</u> range of self-regulation. It is this notion of potential which carries the future orientation. In fact, any particular self-regulating activity is oriented toward the

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[24]William S. Yamamato, "Homeostasis, Continuity, and Feedback," in Yamamato and Brobeck, eds., <u>op. cit</u>., p. 14.

[25]J. H. Woodger, <u>Biological Principles</u> (London: Routledge & Kegan Paul, 1967), p. 5.

disturbance, not the "goal," i.e., steady state. It is the input disturbance which determines the behavior of the physiosystem, not the steady-state. The physiosystem is measured by the amount of input variety for which it compensates.

A self-regulated process is future oriented only in the sense that we can predict the steady-state (on the basis of the past behavior of that process). But in this sense any lawlike or predictable process in science is future oriented. Self-regulated processes are not unique in this regard.

An explicatum should also be precise. Our explicaturm, being a quantitative concept, is more precise, on that basis, than any explicatum offered so far by authors treating the concept of function. Our explicatum, being imbedded in the formal structure of a theory of variety, is precise because of this formal basis. Finally, the interpretation of the theory of variety, and our self-regulation measure, are also quite precise in that straightforward observable variables like temperature or ionic concentration can be used. Adolph has asked: "And now the questions are: how may this recognition of constàncy be removed from the limbo of vagueness, and subjected to quantitative study? What shall be measured to assure us of the concrete existence of regulations?"[26] Our explicatum gives a precise basic answer to these questions.

An explicatum should also be simple. In the various discussions by philosophers on this topic, little unanimity has been reached. One

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[26]Adolph, Physiological Regulations, op. cit., p. 2.

must appeal mainly to the intuition of the reader to judge in this matter. Intuitively, the basic definition of amount of self-regulation, S, is simple. The explicatum can only be as simple however as the criteria of relevance and preciseness permit. Upon examining our explicatum one can see that the complexity it does have is only that needed to insure a relevant and precise explicatum. There is no part of it which could be omitted and still provide a relevant and precise explicatum. In this sense it meets the criteria of simplicity.

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