Chapter 1

# THE NATURE OF HIERARCHICAL CONTROLS IN LIVING MATTER

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## I. The Significance of Hierarchical Control

What is the primary distinction between living and nonliving matter? Is this an arbitrary and subjectivedistinction or can we state clear, physical and mathematical criteria for life? A few decades ago elementary biology textbooks could only approach these questions with a list of imprecise, descriptive properties characterizing life, such as reproduction, irritability, metabolism, cellular structure. Today the corresponding texts give us a detailed list of chemicals, often called the molecular basis of life. Starting with these molecular parts the texts go on to describe how properly integrated collections of these molecules perform most of the basic biological functions. For example, a special collection of amino acids covalently constrained in the proper linear sequence folds up to function as a highly specific catalyst. Similarly a special collection of such enzymes along with special ribonucleic acid molecules can function as a code which correlates the nucleotide triplets with amino acids. An even larger collection of proteins, enzymes, ribonucleic acids, and deoxyribonucleic acid molecules enclosed in a membrane can function as a self-reproducing cell, and a collection of such cells under the control of additional message molecules becomes a coherent organism which can function at many levels in a variety of exceedingly complex environments.

Since the molecules that make up the cell can now be manipulated in test tubes to perform their basic individual functions, it is often argued that the parts which make up living matter do not depend on the living state for their special properties. Or alternatively, it is said that since the parts of living systems behave as ordinary nonliving matter in all chemical details, we have finally reduced life to ordinary physics and chemistry. So then what is the answer to our question? What has become of the distinction between living and nonliving matter?

At the height of success of the revolution in molecular biology, this question simply faded away in the minds of many experimentalists who are concerned only with the detailed molecular basis of life. Now that much of the structural detail has been revealed we are beginning to see again the intricacy of the organization of these parts, and how being alive is not an inherent property of any of the structural units, but is still distinguished by the exceptional coherence of special collections of these units. This is true at many levels of organization, whether the units are monomers, copolymers, cells, organs, individuals, or societies. This coherence among parts has, of course, been given many different descriptions throughout the history of biological science, Concepts such as control, homeostasis, function, integrated behavior, goals, purposes, and even thought require coherent interactions among parts of a collection. The nature and origin of coherent, controlled collections of elements remains then a central problem for any theory of life. What is the basis for this coherence? How do coherent organizations arise from chaotic collections of matter? How does one molecule, ordinary by all chemical criteria, establish extraordinary control over other molecules in a collection? How do normal molecules become special messages, instructions, or descriptions? How does any fixed set of molecules establish an arbitrary code for reading molecular instructions or interpreting molecular descriptions? These are the types of questions which any physical or mathematical theory of life must answer. I have chosen to call this type of coherent collection a *hierarchical organization* and its behavior *hierarchical control*. What I want to discuss is the physical and logical nature of such organizations. In particular I want to emphasize the origin of hierarchical control systems at the simplest level where the necessary conditions are more easily distinguished from the incidental properties.

## II. General Nature of Hierarchical Organizations

There is no mathematical or well-developed physical theory of hierarchical organization or control, so what I have to say will be largely intuitive and descriptive. At the same time I shall use wherever possible the language and laws of physics as a basis for my descriptions. In other words, I am assuming, at least as a working strategy, that there is a physical basis for hierarchical control which is derivable from, or at least reducible to, what we accept already as the basic laws of nature.†

First I would like to distinguish a control hierarchy from a structural hierarchy, since some form of structural hierarchy usually comes into existence before the control hierarchy is established. Structural hierarchies can often be distinguished by their graded size or by the way elements of a collection are grouped. For example the atom, the molecule, the crystal, and the solid can be distinguished as structural levels by criteria of grouping and number; that is, each level is made up of large collection of the units of the lower level. However, there is a more fundamental physical hierarchy of forces underlying these groupings, the strongest forces being responsible for the smallest or lowest-level structures. The strongest force holds together the nuclei of the atoms, and the weakest force holds together the largest bodies of matter. There is also a corresponding hierarchy of dynamical time scales which may be associated with the levels of forces, the shortest time being related to the strongest force and smallest structures, and the longest time related to the weakest force and largest structures. It is because of the separability of these graded levels of *numbers*, *forces*, and *time scales*, or their "partial decomposibility," as Simon [1962] calls it, that we can write

†I do not think that discussion of the exact degree of reducibility of life to physics would be helpful here, although this remains a very profound question. To help the reader interpret my later remarks, however, I should say that on the one hand, according to my idea of physics, I do not believe that molecular biologists have now reduced life to physics and chemistry, which many have claimed [see, for example, Watson, 1965; Crick, 1966], or that they will have no difficulty in doing so [see, for example, Kendrew, 1967]. I have given my reasons for this belief elsewhere [Pattee, 1968, 1969a, b]. On the other hand, I see little hope of explanatory theories or experiments arising from the other extreme attitudes, that we can only give necessary but never sufficient conditions for life [see, for example, Elsasser, 1969], and that life is a process which, while obeying all the laws of physics, can never be completely explained [see, for example, Bohr, 1958]. While there well may be some degree of truth in these attitudes, they do not appear to be a productive strategy at this time. In other words I regard a fundamental description of life as neither a simple problem close to solution, nor an irreducible problem with no solution. Rather I believe that it is a deceptively difficult problem which will take a large amount of effort before it is clarified. Sommerhoff [1959] in his book *Analytical Biology* has stated the problem with great care, but as he says, he does not claim to have a physical answer, only a clearer mathematical characterization of the difference between living and nonliving matter.

approximate dynamical equations describing one level at a time, assuming that the faster motions one level down are averaged out, and that the slower motions one level up are constant. Furthermore, since the forces and constraints between particles at one level have no special structure we may also use the approximation that one particle is typical or representative of any of the particles in the collection. It is only because of these approximations that our solution to a one- or two-body problem come close to our observations, and that many-body problems can be treated at all.

Hierarchical control systems are much more difficult, since they involve specific constraints on the motions of the individual elements. In a control hierarchy the collective upper level structures exert a specific, dynamic constraint on the details of motion on individuals at the lower level, so that the fast dynamics of the lower level cannot simply be averaged out. This amounts to a feedback path between two structural levels. Therefore, the physical behavior of a control hierarchy must take into account at least two levels at a time, and furthermore the one-particle approximation fails because the constrained subunits are atypical.

The epitome of hierarchical control in biology is the development of the multicell individual from the germ cells. Here the lower-level element is the cell itself. As a separate unit each cell has a large degree of autonomous internal activity which involves deeper hierarchical levels of control. These activities include growth and self-replication. However, as these cells form a physical aggregate, there arise new constraints which limit the freedom of the individual cells. Some of these constraints are of obvious physical origin such as the restriction of spatial freedom by neighboring cells of the collection. Such *structural* contraints may cause cells to stop growing and replicating because of simple overcrowding or lack of food. But these restrictions are not different from those found in a growing crystal. The *control* constraints, on the other hand, limit the individual cells' freedom in a very different way. We observe that as the collection of cells grows, certain groups of cells alter their growth patterns, depending on their positions in the collection, but not because of any direct physical limitation in food or space. The control constraint appears in the form of a message or instruction which turns off or on specific genes in the individual cells. This is a fairly clear example of hierarchical control, but how is this type of switching constraint to be distinguished from the constraint of simple crowding? In other words how can we distinguish physically between structural constraints and hierarchical controls?

There is no question, of course, that hierarchical constraints have a structural basis. That is, the molecules which turn off or on specific genes of the cell have definite structures which are responsible for the recognition of the target gene as well as the masking or unmasking of this gene. So why do we call this molecule a hierarchical rather than a structural constraint?

One way of expressing this difference between hierarchical and structural constraints is to say that structural constraints permanently eliminate or freeze out degrees of freedom, whereas hierarchical controls establish a time-dependent correlation between degrees of freedom. We could also say that structural constraints reduce the possible number of states available to a system of particles because of the inherent or unconditional dynamical or statistical laws of motion of the particles, whereas hierarchical constraints select from a set of possible states because of relatively fixed but conditional correlations between the particles of the collection. But obviously there are many possible conditional correlations. Which ones constitute a hierarchical control system? We feel intuitively that hierarchical control must result in some form of organized behavior of the total system, but what does it mean to say that there is organized behavior? Another way of saying this is that structural organizations often appear without having any function while hierarchical control systems always imply some form of function. But again since function is no better defined than organization, in any physical sense, this distinction is not much help. In many discussions of self-organizing systems we find the concept of *information* introduced in order to clarify this same distinction. For example, we say that hierarchical control is accomplished by information or messages which act as a constraint on a variety of possible configurations of the system. However, this language is usually ambiguous because it is also quite correct to say that a structural constraint uses information to constrain the variety of configurations. Therefore, while I believe that the concept of informational constraints is necessary in order to understand what we mean by a hierarchical control system, the problem is not clarified until we can say what type of information we are talking about. Specifically, we must distinguish between structural and hierarchical information.†

## III. Hierarchical Control Implies a Language

The basic idea I want to express is that hierarchical control in living systems at all levels requires a set of coherent constraints which in some sense creates a symbolic or message content in physical structures, in other words, a set of constraints which establishes a *language structure*. Now immediately one might object to this idea on the grounds that I have said that I was trying to

†Such distinctions, of course, always need to be made and it is a common weakness of the use of information theory in biology that there is no way to evaluate objectively the significance of information. There are several precise measures of purely symbolic information [see, for example, Abrahamson, 1963]. and also purely physical entropy [see, for example, Brillouin, 1962]; but relating the symbolic information with the real physical event it stands for always requires a very complex transducer, such as a measuring device, a pattern recognizer, or an observer.

explain hierarchical organization in terms of more elementary concepts of physics and mathematics, and yet now I want to talk about symbols and language structures which appear to be more abstract and less well understood than many of the simpler integrated control systems we are trying to describe. Furthermore, it might be argued that our language structures are really the final outcome of billions of years of evolution and therefore could not have had much to do with the first question we asked, namely: What is the primary distinction between living and nonliving matter?

I prefer to turn these arguments around. I would agree that the fundamental nature of language is indeed less well understood than the nature of physical laws, but I would not agree that the apparent abstract, logical structure of language implies that language is not dependent on a physical embodiment or a molecular basis, which in every detail must follow the laws of physics and chemistry. The problem, as I see it, is that language has been studied with too much emphasis on its abstraction and too little attention to the common characteristics of actual physical constraints which are needed to support any language structure.

The second argument that language structure appears at the final outcome of billions of years of evolution is no evidence at all of the irrelevance of more primitive language constraints at the origin of biological evolution or at any hierarchical interface where a new functional level of description is necessary. On the contrary, the only generally acceptable condition for a living system capable of biological evolution that I know requires the propagation of genetic messages that could only make sense because of the integrated constraints of the genetic code and the reading and constructing mechanisms that go with it. Furthermore, as I shall explain below, the very idea of a new hierarchical level of function requires what amounts to a new description of the system, and any idea of a *description* is only meaningful within the context of a language.

I am using language here in its broadest functional sense, and I am interested in describing language structures in their most primitive form. Many classical linguists may object to this use of the word which they prefer to reserve for the unique, learned, symbolic activity of humans. Mathematical linguists also may object that without a formal definition of my idea of language this usage will not be productive. I am not thinking of language in either the anthropomorphic or formal sense, but as a *natural event* like life itself which needs to be studied in the context of natural laws from which it arose. Formalizing a language is useful for well-defined tasks, but in our case premature formalization would only be at the expense of ignoring the physical origin and basis of the natural rules and symbols of the most elementary language systems. Similarly restricting the concept of language to human communication eliminates from study the many stages of evolutionary hierarchies or symbol-manipulating systems which were responsible for creating this latest and most complex symbolic formalism of man.

The integrated records, descriptions, and instructions in cells are no less a language system because we know the molecular structure of some of their coding devices and symbol vehicles. But while many biologists more or less metaphorically think of the genetic processes as the "language of life," the full necessity of an authentic language system for the very existence of life, which I am proposing, is seldom recognized. In biological studies at all levels of organization we find the same implicit recognition of language-constrained behavior, such as references to hormones, chemotactic substances, and controllers of genetic expression as message molecules. Longuet-Higgins [1969] has emphasized this essential dependence of all levels of life on symbolic instructions by practically defining life as "programmed matter." However there is almost no discussion of why a particular chemical reaction is regarded as a message or an instruction. All the attention is on the chemical structure of the message vehicle and its interactions with its target, or on the formal, mathematical modeling of this process. What we need to know is how a molecule *becomes* a message [Pattee, 1970a].

To justify the study of hierarchical theory as a complement to this current emphasis in biology on detailed physical and chemical structure, we must show clearly why a knowledge of structure alone, however complete does not include an understanding of the basic nature of life. The justification, as we shall see, is very similar to the reason we cannot understand the basic nature of computation only by looking at the physical structure of a particular computer, or the reason we cannot understand the nature of language only by a detailed description of the symbol vehicles and rules of grammar of a particular language. In order to show how hierarchical interfaces are supported by language structures we first will look more carefully at the general properties of language and hierarchical control systems.

## IV. Some Basic Properties of Language and Control Hierarchies

Both languages and hierarchies must ultimately be created and supported by material structures that are described physically as coherent collections of constraints. In human languages the rules of grammar are many levels of abstraction removed from the simplest physical constraints. Similarly, in human hierarchies the rules of tradition, custom, or legal systems apparently have nothing directly to do with physics. Nevertheless, they function as a limitation on the freedom of individual elements of a collection, and as with all symbols, at some deep level they must have a material counterpart. These rules are only at the top of a hierarchical structure of many levels, and I believe that they are far too complex to usefully discuss in any physical language [see Platt, 1969].

We want to look at the basic nature of much more primitive languages and hierarchies. In fact, I think that it is a valuable strategy to ask what is the simplest possible set of constraints on a collection of elements which would justify calling the collection a language or a control hierarchy. If we do not place such a severe limitation on our study of the nature of languages and hierarchies, we will be faced with an apparently inexhaustible complexity in which details cannot be clearly recognized as incidental "frozen accidents" or as essential conditions. That is why we choose to concentrate on the simplest cases.

However as a functional criterion for assuring ourselves that we are not oversimplifying, we shall require that the simplest languages and hierarchical organizations have an evolutionary potential. In other words, a language must be able to change continuously and persistently without at any point losing a grammatical structure defining the meaning or consequences of its descriptions. This continuous change and growth is observed in all higher natural languages, and it appears that use of the concept of language would be very difficult to justify in any system of constraints that did not have this property. Similarly any hierarchical organization that did not have the potential for establishing new levels of function and control would hardly be of biological interest. In other words, what we are saying is that life is phenomenologically distinguished from nonlife by its ability to evolve level upon level of hierarchical functions. Our problem is to understand the basic conditions that make this possible at the most primitive level.

### A. Some Properties of Language

Human written languages are not associated with their particular physical representations. That is, we do not consider the type of paper, ink, or writing instruments as crucial properties of the language structure. Spoken languages, since they are more primitive, are more easily analyzed within the context of the physiological structures which make them possible [see, for example, Lenneberg, 1967]. Nevertheless, the universal properties of languages are all the more remarkable in view of their many divergent origins.

Six properties of language have been suggested by Harris [1968] in his book *Mathematical Structures of Language*. There may be some exceptions to these properties especially if we extend the meaning of language, as we propose to do, to include much more elementary symbolic control systems. Even so, these properties of higher languages serve very well as a basis for our discussion of more primitive language structures.

1. *The elements of language are discrete, preset, and arbitrary.*

The elements here can be regarded as the letters of an alphabet or the basic symbols or marks which can be arranged in patterns to form sentences, messages, or instructions. The idea of preset elements may be replaced in primitive symbol systems by the idea of stability in time of the symbol vehicles relative to the duration of the messages formed with them. The most difficult concept here is "arbitrary." Arbitrary according to the dictionary can mean chosen by the decision of an arbitrator who has such authority, or arising from caprice without reason. The mathematical connotation of an arbitrary choice is that there exists no significance to the choice except that it must be made decisively. Now in the case of primitive languages there is obviously no outside arbitrator to make the first choices of alphabets or grammars. On the other hand, we find it difficult to imagine a coherent language structure or a hierarchical organization with the potential for evolution arising solely by caprice or chance. Futhermore, from the physicist's point of view, if one chooses to consider any collection of matter in maximum detail, then the concept of arbitrariness does not apply, since the laws of motion leave no room for external arbitration or capricious choices. Arbitrariness in elementary physical systems can arise only because of ignorance of initial conditions or because of uncertainty in measurements. As we shall see when we discuss the properties of hierarchies, the very concept of arbitrariness in physics requires an *alternative description* to the description at the deepest dynamical level.

2. *Combinations of elements are linear and denumerable.*
3. *Not all combinations of elements constitute a discourse.*
4. *Operations which form or transform combinations are contiguous* (*that is, there is no metric as in musical notation; "distance" between symbols is just equivalent to the symbols in between them*).

These properties effectively isolate language vehicles from the ordinary limits of space and dynamical time of simple physical systems. Since the individual elements are fixed structures, they are independent of time and since they are strung together linearly, spatial restrictions on their order is not as important as it is in normal three-dimensional collections of matter. Condition 3, not all combinations of elements constitute a meaningful statement, reflects only the rules of grammar that are embodied in the special constraints of the language. These rules may also appear arbitrary to a large extent. At least they are not a direct or obvious result of any laws of nature.

Since the transformations on these combinations of elements must nevertheless be definite, it is essential that the combinations function as complete messages independent of real physical time. This leads to Condition 4, which places the operations on the elements under sequential control, and removes the dependence of their transformations on the real time of physical equations of motion.

These four conditions also create the apparent separation between formal, logical systems and physical systems, or between abstract automata and the real machines which approximate their behavior [see von Neumann, 1956]. Our problem is to explain how such properties which seem to separate symbolic operations from ordinary physical transformations can actually grow out of physical systems.

The last two properties of languages are much harder to define or understand, but are the most important properties for the type of evolution we find in living systems.

5. *The metalanguage is contained in the language (that is, the language can make statements about itself, its grammar, its symbols, or any constraint from which its grammar or symbols is formed).*

A most important type of statement which facilitates this property is the *classification*, for example, "*X* is a word," or "UGC is a codon," One could argue that classification is the most fundamental operation of logic, mathematics, and language. Classification requires a set of rules for distinguishing alternative events or structures, and in symbolic systems formation of these rules usually appears arbitrary but definite.

When speaking of real physical systems, however, the concept of classification, like arbitrariness, can only arise in the context of a measurement process or an observation. This is true because of the fundamental nature of physical laws which state that either no alternatives exist, as in classical determinism, or that every alternative must be considered as equally probable, as in quantum mechanics. Only when a measurement is performed do we have additional rules which create classifications, and these rules are not derived from the equations of motion but from the constraints of the measuring device or the observer. Therefore, the physical origin of natural or spontaneous classification rules has many of the same difficulties as the origin of language. I believe, in fact, that a good case could be made that any classification process which actually performs the classification in a physical system (that is, a measurement process) presupposes some form of language structure [Pattee, 1971].

6. *Language changes gradually and continuously without at any point failing to have a grammatical structure.*

This is very similar to the continuity principle on which we base our thinking about evolutionary processes. For example, it is difficult to believe that the genetic code arose complete, as it now exists, through an abrupt, discontinuous act of creation. Any alternative continuous process, on the other hand, must at all stages constitute a viable coding system. This implies that whatever message sequences occur, there must be a definite rule for classifying them as nonsense or not, and if not, then complete rules for translating the message into functional proteins. This does not mean that primitive messages themselves cannot be very simple, but it does set limits on the logical simplicity of the first set of constraints which form the language grammar [Pattee, 1972].

With regard to language, Harris [1968] says this evolutionary property implies that at any given time the grammatical rules must be describable correctly in at least two different ways, so that there can be functionally complete overlap between old and new descriptions. We shall see that this condition is related to the principle of descriptive and structural equivalence which is necessary for evolution in hierarchical control organizations.

## B. Some Properties of Control Hierarchies

A hierarchical control system is a more concrete and mechanical concept than a language structure, and I am not suggesting that the two concepts are equivalent. What I hope to show is that they are so intimately related that one cannot exist without the other—at least the most basic parts of the other. Furthermore, I would expect what we do not fully understand about the natural origin and evolution of languages is often hidden in the constraints of a real physical hierarchical control system; and similarly, what we do not appreciate about the coherence of function in biological hierarchies is hidden in the descriptive constraints of a symbolic language structure.

1. *A control hierarchy constrains the behavior of the elements of a collection so that they perform some coherent activity.*

We are speaking here of autonomous hierarchies, so the constraints must arise within the collection itself and not from an outside authority. The concept of constraint in common language implies an enforceable limitation of freedom. The nature of constraints in physical language requires more elaboration, since constraints are not considered as a fundamental property of matter. One does not speak in physics of forces of constraint limiting the freedom of astronomical or atomic bodies, even though the forces between so-called "free" particles define the motions. In fact, as we pointed out earlier with regard to the concept of arbitrariness, the problem is that the dynamical level of description leaves no freedom at all. So what is the meaning of "additional constraints" when the dynamics leaves no alternative?

The answer is that the physical idea of a constraint is not a microsopic dynamical concept. The forces of constraint to a physicist are unavoidably associated with a new hierarchical level of description external to the system. Whenever a physicist adds an equation of constraint to the equations of motion, he is really writing in two languages at the same time, although they may appear indistinguishable in his equations. The equation-of-motion language relates the detailed trajectory or state of the system to dynamical time, whereas the constraint equation is not about the same type system at all, but another situation in which some dynamical detail has been purposely ignored, and in which the equation of motion language would be useless. In other words, forces of constraint are not the detailed forces between individual particles, but forces from collections of particles, or in some cases, from single units averaged over time. In any case the microscopic details are replaced by some form of statistical averaging process. In physics then, a constraint is a reinterpretation or reclassification of the system variables. A constraint is distinguished from what it constrains only by the fact it requires a different type of description.

Since we regard hierarchical control as a special set of constraints, it follows that a single level physical description of a hierarchical organization cannot begin to explain its behavior. Rosen [1969] has put this even more strongly, almost as a definition of hierarchy: "... the idea of a hierarchical organization simply does not arise if the same kind of system description is appropriate for all of [its activities] [p. 180]," and in other words, "... we recognize [hierarchical] structure *only* by the necessity for different kinds of system description at various levels in the hierarchy [p. 188]."

Now I do not mean to imply that the use of alternative descriptions is easy to understand and represents a physical reduction of the problem of hierarchies. On the contrary, even though physicists manage quite well to obtain answers for problems that involve the dynamics of single particles constrained by statistical averages of collections of particles, it is fair to say that these two alternative languages, dynamics and statistics, have never been combined in an entirely unified or elegant way, although many profound attempts have been made to do so. How well the dynamical and statistical descriptions have been related is, of course, a matter of opinion. The basic problem is that dynamical equations of motion are strictly reversible in time, whereas collections of matter approaching an equilibrium are irreversible. The resolutions of this problem have been central to the development of statistical mechanics, and have produced many profound arguments. For our purposes we need not judge the quality of these arguments, but only note that the resolutions always involve *alternative descriptions* of the same physical situation [see for example, Uhlenbeck and Ford, 1963]. Furthermore, the problem has proven even more obscure at the most fundamental level, namely, the interface between quantum mechanics and measurements statistics. This is known as the problem of quantum measurement, and although it has been discussed by the most competent physicists since quantum mechanics was discovered, it is still in an unsatisfactory state. Again, what is agreed is that measurement requires an *alternative description* that is not derivable directly from quantum mechanical equations of motion. The quantum measurement problem is closely related to the statistical irreversibility problem, and it too, has a long history of profound arguments central to the interpretation of quantum theory. The basic difficulty here is that a physical event, such as a collision of particles, is a reversible process, whereas the record of this event, which we call a measurement is irreversible (the record cannot precede the event). Yet if we look at the recording device in detail, it then should be reducible to reversible interactions between collections of particles. The difficulty also has to do with the fact that all mechanisms for control or recording require path-dependent, nonintegrable (nonholomonic) constraints, and thus far such extra relations between conjugate variables cannot be introduced into quantum mechanical formalism without basic difficulties [see, for example, Eden, 1951]. Again, for our discussion here it is not necessary to judge the many attempts to resolve this difficulty since as a practical matter they all involve alternative descriptions for the event and the record of the event, [for example, see von Neumann 1955] for a detailed treatment, or Wigner [1963], for a nonmathematical review of the problem. For a discussion of quantum measurement and biology see Pattee [1971].

So much for the physical basis of constraints, which in the context of biological organizations clearly needs some fundamental study. But what about coherent activity? What does this mean? Coherent usually implies a definite phase relationship between different periodic phenomena. I would like to extend the meaning of phase, which normally depends on real physical time, to include sequential order. I would also like to extend the idea to nonperiodic events. Thus, I would call any switching network or sequential machine a coherent set of constraints. This leads to the second property of control hierarchies:

2. *The coherent activity of the hierarchical control system is simpler than the detailed activities of its elements.*

This implies that some detail is selectively lost in the operation of the constraints.

The important point here is that constraints select which details of the elements are significant and which details are irrelevant for the collective behavior system. I want to stress that this selection in living systems is not dependent on the criteria invented by an outside observer as it is for artificial machines, although an outside observer may be clever enough to see the significant variables and thereby greatly simplify his description of the living system.

Hierarchical control therefore implies much more than a transition from a microscopic, deterministic description to a statistical description. Rosen

[1969] has used this transition from particle dynamics to thermodynamics as the only example known to him of an honest physical solution to the problem of how apparently independent system descriptions for different activities of the same system are actually related. This example is not, however, a hierarchical control system since the choice of the thermodynamic variables has no constraining effect on the microscopic degrees of freedom. Therefore, no matter how logical, practical, or even inescapable the choices of variables may appear, they must still be regarded as the physicists' choice and not the systems' choice.

The simplest natural example I know of a complex dynamical system which has a simple, collective activity is an enzyme molecule. The enzyme considered in maximum detail collides with molecules of all kinds with no regular, simple results. Only when a particular type collides with the enzyme will the simple, regular activity occur which we call a specific catalytic event. It is significant that just as the gas laws were discovered before the underlying dynamics, the enzymes were first discovered by their functional behavior; only, in the case of enzymes, we have not yet managed to completely explain the behavior by an underlying dynamical model. The behavior of enzymes also suggests two more very important properties of control hierarchies:

3. *Hierarchical constraints classify degrees of freedom to achieve selective behavior.*

Classification is another way to say that there has been a selective loss of detail. In dynamical description all degrees of freedom are treated equally. A constraint recognizes or selects some degrees of freedom as crucial for its collective activity and largely ignores the others. We also can say that the coherent activity of the collection is sensitive to some degrees of freedom and insensitive to others. The enzyme is a remarkably insensitive mechanism with respect to a large variety and number of nonsubstrate collisions which it must withstand. We call this its high specificity. It is also incredibly responsive to the sensitive properties of its particular substrate. The magnitude of this response we call its catalytic power.

A typical example of an artificial or externally designed hierarchical control is the traffic light whose timing responds only to sensors in the road. Such a signal system, like the enzyme, very strongly controls the rate of specific events on the basis of a few sensitive degrees of freedom, and completely ignores an enormous variety of other variables.

4. *Both the selection of sensitive degrees of freedom (or the choice of relevant variables), and the mechanism which performs the selective activity appear largely arbitrary.*

The arbitrariness of traffic signals is quite obvious. With living hierarchies there is room for differences of opinion. What we know about functional arbitrariness of enzymes is still very little. However, it does not strain our imagination to consider the possibility that an enzyme could be designed to recognize almost any substrate and catalyze almost any bond with almost any arbitrary correlation between the recognition and catalytic steps.

It is this type of *arbitrary* but *definite* constraint that correlates a structure and an operation which I would call the fundamental property distinguishing symbolic aspects of events from the physical interaction which underly these events. Clearly at least two levels of external description are necessary to describe this happening in such a system, since as we have explained, the constraint itself is not derivable from the microscopic dynamical equations of motion. The basic problem is the source of this arbitrary definiteness when there is no external observer or designer. If arbitrary, alternative correlations are physically possible, then what is it that determines which alternatives are fixed as the "rule of operation?" This is the central problem of the origin or source of hierarchical organization, for it is precisely this choice of arbitrary correlations between the elements of a collection which determines the type of coherent behavior or the integrated function of the collection.

This problem is often evaded by saying that the choice is made by some information in the form of other structures of the system such as the genetic deoxyribonucleic acid that determines which enzymes are to be constructed. But clearly the deoxyribonucleic acid is just another arbitrary but definite constraint that has informational significance only because of the arbitrary but definite enzymes and transfer ribonucleic acids of the genetic code. At present, the origin of this complex, coherent system of constraints is totally unknown. It is my guess that to understand the origin of the code we will have to understand more basic principles of the origin of language and hierarchical control systems.

The four properties of control hierarchies I have described might be called operational properties. Like the first four properties of language they serve primarily to distinguish physical processes from functional processes, or perhaps material systems from symbolic systems. More precisely these conditions separate physical behavior from the symbolic or functional behavior of material systems.

Again, as with the last two principles of language, the last two observed properties of biological hierarchies have to do with their evolution. They are, in fact, somewhat in parallel with the language properties.

5. *New hierarchical constraints can continue to appear at higher levels without destroying the existing constraints at the lower levels.*

This more or less obvious property of living organizations expresses the continuability or recursiveness of hierarchical origins [Bianchi and Hamann, 1970]. Hopefully, this recursive property suggests that if we could discover how *any* new functional organization or new classification is created spontaneously from a set of more or less disordered elements, we could generalize this discovery into a theory of hierarchical origins.

The corresponding property of languages follows from the fifth property, that natural languages contain a metalanguage. This is also a continuable or recursive property that allows us to say whatever we wish *about* what we have just said—no matter on how abstract a level we may have said it—while still retaining the same fixed and finite set of grammatical rules and arbitrary symbols. In other words, natural language always permits new classification and new interpretation of its structures, even though its substructure remains fixed. This is a most remarkable property which is not fully understood. This ability of descriptions is most carefully analyzed in the notion of *effective computability* in the theory of automata where there are very strong arguments, originating with Turing [1936], that one fixed and finite language could effectively describe all imaginable effective procedures in any language [see Minsky, 1967].

There is certainly some relation between these recursive properties of languages and hierarchical organizations; but unfortunately in both cases there are many mysterious points. In particular, the origin of this property or even the necessary conditions for the simplest cases of this property in both languages and hierarchical organizations remain unclear.

We can say something, however, about the relation between this new-interpretation property of language and new-function property of hierarchical levels. We have emphasized that from the physical viewpoint a new hierarchical level is recognized only when a new description of the system exists. Since the old description is assumed to be complete for the variables of the previous level, the new description must be based on a new classification of the variables at the previous level. But a new classification is exactly what a natural language can accomplish. Therefore, a language structure rich enough to reclassify its own symbols is, at least formally, a sufficient set of constraints to allow the creation of new hierarchical control levels.

The primeval origin problem is still with us, however, since, as we also emphasized, no language can be realized without a coherent set of material constraints to support its syntactical rules and symbol vehicles. This means that the physical embodiment of any language is itself a hierarchical set of constraints. In other words, the apparently endless variety of functions at all levels of biological organization could be generated under a fixed and finite set of coherent physical constraints which we would call a realization of a language, but obviously we cannot explain the origin of the first set of such constraints by the same generation process. To me this is the chicken–egg aspect of the matter–symbol paradox at the most physical level I can imagine it; but hopefully it is at a sufficiently well-defined level to suggest clues to its solution.

The last property of functional hierarchies I consider so essential for the origin and evolution of life that I would be inclined to elevate it to a principle of structural and descriptive equivalence. I would state it as follows:

6. *There are many physical structures that execute the same function; and there are many descriptions of the same physical structure.*

Examples of this principle are found at all levels. At the level of artificial control systems, from simple switches to entire computers, we know that there are many devices using quite different principles which perform equivalent functions. We also know that these devices can have equivalent alternative descriptions within one language, and of course also in other languages.

At the deeper and more primitive levels of molecular control hierarchies, this principle implies that the function of a genetic code can be achieved through equivalent sets of enzymatic constraints, and furthermore that the structure of one enzyme can have equivalent descriptions. Of course, the principle also implies that the same enzymatic function can be achieved through equivalent structures.

The last two implications we know are, in fact, the case. There is more than one sequence of nucleotides that will produce the identical amino acid sequence, and there is more than one amino acid sequence that will have identical enzymatic activity. There is no direct evidence that more than one genetic code could produce the identical form of life. But there is really no direct evidence against it either, since we have only one case. At least from our present understanding of the mechanism and structure of the transfer enzymes and transfer ribonucleic acids, there is no known physical, chemical, or logical reason why equivalent alternative codes could not occur in principle.

There are several ways to see why this property or principle is likely to be fundamental for the origin and evolution of hierarchies as well as languages. First, it would relieve the well-known problem of the spontaneous appearance of a particular structure which is highly unlikely as judged successful by only structural criteria. The principle replaces structural success by functional success. The corresponding reduction in the size of the search space depends on how broadly or narrowly we choose to define our function. For example, if we ask for the probability of the spontaneous occurrence of a hammer, we will find it high if almost any hard, dense object that we can lift easily will pass our functional needs. But if we also need the function of pulling out nails, the probability will drop enormously. What we must understand in the case of the origin of languages and hierarchies is nature's broadest criteria for functional success. Specifically, with origin-of-life experiments, this property suggests that too much emphasis on the similarity of molecular structures in abiogenic sythesis experiments is literally making life difficult.

The theory of evolution may also need this principle of structural and descriptive equivalence. The problem is well known: How does natural selection confer stability on all intermediate evolutionary steps leading to some integrated function? The mathematical equivalent of this problem is: How do random search and optimization procedures keep from being trapped at local maxima [see, for example, Bossert, 1967; Schutzenberger, 1967]? The formulation of this search problem usually involves an assumption that there is a purely physical configuration representing adaptedness or fitness, and for each configuration there is a value for the fitness which can be optimized by some form of search through the physical configurations. As we have seen, however, function and therefore fitness depend upon the *choice of description* of the physical configuration. Now, by the principle of equivalence, a new description need not change the local function, but in general a new description will alter the value of fitness in the neighborhood of a given function. In other words, the evolutionary search strategy may be primarily for descriptions of functions which do not lead into local traps. This is the same logic used by Harris [1968] to explain how language grammars can evolve. This must also be a continuous process; that is, at no stage of evolution can there fail to be a correct and complete description of the rules of grammar. It is observed, however, that at a time $t_1$ a given rule has a description $D_1$, and at a later time $t_2$ this rule has changed and has a new description $D_2$. Since for all times in between $t_1$ and $t_2$ there must be a complete description. it follows that $D_1$ and $D_2$ overlap. This is true for all times, from which it follows that all rules of grammar must always have at least two correct descriptions.

The point I wish to emphasize is that if life is at its foundation a set of descriptive constraints on matter, then its evolution need not be restricted to search and selection under one simple physical measure of fitness, but may have many simultaneous, partially overlapping descriptive measures on which natural selection may operate. This also suggests that instead of trying to understand complex higher learning processes by imitating an oversimplified model of evolution, we may be justified in applying some basic properties of language structures to help understand the apparently primitive evolutionary processes which may turn out to be not so simple. This does not, of course, get to the root of the problem of the origin of primitive language structure.

Let us return to the physical basis of languages. How are the properties of languages and hierarchies, outlined in this section, embodied in real, physical constraints? What are the physical conditions which satisfy these properties?

## V. Physical Conditions for Language and Control Hierarchies

The fundamental general physical requirement for languages and hierarchies are constraints—in particular, fixed and finite sets of conditional constraints, Purely structural constraints, which permanently remove degrees of freedom, are necessary to support conditional or time-dependent constraints, but structural constraints alone cannot produce what we recognize as the rules or classifications necessary for languages or hierarchical controls.

The first property given for a control hierarchy was that the collection of elements performs some coherent activity. I extended the meaning of coherent to include nonperiodic variables and nondynamical (sequential) time scales. But what does this imply about the physical condition?

The loss of dynamical time in the description of a physical system means that some degrees of freedom or some detail has been ignored, usually by an averaging process (either number or time averages). However, detailed coherence in time has certainly also been lost by this process, so under what conditions do we expect sequential coherence to arise? Now sequential coherence means that events take place in a *definite order*, but this implies that there are such things as *definite events.* In a continuous statistical description we can get definite events only by threshold or trigger phenomena. Such events are also described as cooperative events, but the essential point is that they are irreversible and therefore dissipative. This means that sequential coherence is subject to noise (fluctuations). This is not the same as saying that *measurement* of sequence is uncertain, the way we say the measurement of dynamical variables, such as time, is uncertain. It means that the sequence itself is not precisely defineable. This places fundamental limits on the reliability of all hierarchical controls as well as on all realizations of formal logical systems that require sequential coherence in their symbolic transformations [Pattee, 1969a].

The second property of hierarchical control is that the collective functional activity is simpler than the underlying dynamics. This does not in itself lead to any profound physical condition. It implies however that there is some definite, regular process for averaging or ignoring the dynamical detail within the system itself. As we mentioned before, the pressure in a gas is independent of dynamical detail, but this detail is ignored only by the outside observer in the sense that there is no difference whatsoever on the dynamics because of the new description of pressure.

It is only when this property is added to the third property that simplification has physical meaning. The third property states that the constraint *classifies* the detailed degrees of freedom. This implies fixed rules of interaction that determine which degrees of freedom are effective in triggering the operation of the constraints. This is what separates *signals from noise*, and therefore this classification represents a very fundamental interface, inseparable from the more general matter–symbol interface.

What are the necessary physical conditions for a natural classification process? To classify means to distinguish between elements or events according fixed rules, but in the primitive context we are discussing, to distinguish must also imply definite physical change on the classified elements, such as marking or separating them from the collection. In other words, after the classification is completed, there must be a relatively permanent physical result which would not have occurred if the classification had not taken place. Before the classification there must be a distinguishing rule, and after the classification there must be a record to show that the rule was actually applied.

The question always arises why we cannot use this same description for a simple two-component chemical reaction, $A + B \rightleftharpoons AB$. We may assume that A collides with many other non-B molecules but does not react with them. Therefore, we could say, as above, that A has "classified" its collisions, and when it "recognizes" a B-type molecule, it forms a permanent bond with it, thereby establishing a "record" of the classification.

This alternative description may appear to be a gratuitous elaboration on what is acceptable physical or chemical language. But the basic question is whether in more complex situations, such as the enzyme catalyzed reaction, it is not equally gratuitous to say that the enzyme classifies or recognizes the substrate. In other words, is there some natural physical condition which distinguishes simple collisions from classifications in chemical reactions?

I believe that there is a condition, but just how it relates to physics remains to be explained. The condition that distinguishes collisions from classifications is precisely the same condition that separates physical interactions from symbolic constraints and events from records of events. The central condition is *arbitrariness*. As I said before, I believe it is the existence of an *arbitrary* but definite constraint correlating a structure and an operation which creates the symbolic aspect of physical events. Such constraints require an *alternative description*. This description is not to be associated with an outside observer or with his highly evolved language, but with a coherent set of constraints inside the system which fulfill the conditions of a language structure. These constraints are also arbitrary to some extent. As individual constraints they must appear as frozen accidents, but as collections they must appear integrated and functional.

## VI. Conclusions

The most positive conclusion I can make is that life and language are parallel and inseparable concepts, and that the evolution of the many hierarchical levels uniquely characteristic of living organisms depend on corresponding levels of alternative descriptions within a language system. According to my picture, it is just as close to the truth to say that biological evolution is the product of natural selection within the constraints of a language as it is to say that language is the product of natural selection within the constraints of living organizations.

My most negative conclusion is that we still have too narrow and ambiguous a concept of language to come to grips with its relation to natural laws. We do not understand the physical basis of symbolic activity. Moreover, it is not at all clear at this point how difficult a problem this may turn out to be. The history of the matter–symbol paradox certainly should give us great respect for its difficulty, but I do not see how we can evade the question and still understand the physical basis of life.

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