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Principles of Systemic Control:
The implications of dual control in natural systems for the design of artificial systems

Norman D. Cook

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ATR人間情報通信研究所

〒619-02 京都府相楽郡精華町光台2-2 ☎07749-5-1011

ATR Human Information Processing Research Laboratories

2-2, Hikaridai, Seika-cho, Soraku-gun, Kyoto 619-02 Japan

Telephone: +81-7749-5-1011
Facsimile: +81-7749-5-1008

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Summary

The long-term survival of natural systems requires a balance between informational stability, on the one hand, and the ability to alter and use that information, on the other hand. The predominant natural systems on Earth have found a means for balancing these contradictory tendencies by having a "dual" control mechanism: two physically similar control components that are specialized for maintenance of the stability of the system and contact with the external world, respectively. Examples can be found in atomic physics, cell biology, human neuropsychology and cybernetics. The importance of dual control is outlined and its implications for the design of intelligent machines discussed.

Key words: atom, cell, human organism, neutrons, protons, electrons, DNA, RNA, protein, cerebral hemispheres, corpus callosum, handedness, speech, laterality, cybernetics, goal-directed system, stability, flexibility, isomorphism

I. Introduction

In the design of artificial systems, a fundamental question concerns the degree to which specific control mechanisms must be imposed on the system. In traditional artificial intelligence (AI), all mechanisms are explicitly coded, and there is no room for the system to discover new facts or learn new relationships. Even in the so-called hybrid systems, where a neural network is employed to learn new facts about the system's environment, the architecture of the system and the relationship between the traditional AI components and the neural net are predetermined. The opposite extreme of such imposed structure can be seen in current work on cellular automata, where the underlying assumption is that an absolute minimum of control should be given to the system. On the contrary, once rules for the activity, random mutation and replication of a fundamental segment of code have been provided, the system itself must evolve whatever mechanisms of control are necessary by means of natural selection. This approach is inherently optimistic concerning the possibility that, given the basic constraints of the system, sufficient organization will evolve and the system will become something more than an undifferentiated mass of isolated cells without any coherent, higher-level organization.

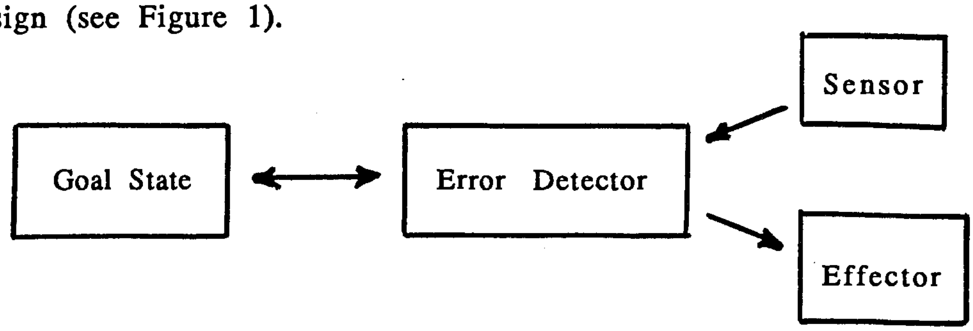
While few researchers are today optimistic about the possibilities for true intelligence emerging from traditionally-programmed AI systems, it is difficult to determine on *a priori* grounds whether or not the uncontrolled cellular automata approach will evolve higher level structures. It may therefore be worthwhile to examine the kinds of control structures which are known to have emerged at various levels of organization to see what might be learned about the control of complex systems. At worst, we will accumulate a variety of examples of successful control mechanisms, each of which is specific to its particular domain. At best, however, we may deduce general principles of control which can be implemented in artificial systems. Implementation of such principles must of course be undertaken at a low enough level that explicit control of the evolution of the system is not necessary, but still providing some structure for the coordination of a complex, many-body system.

It is important to keep in mind that the specific examples of control structures in the worlds of physics, biology, psychology, etc. are necessarily determined by the nature of the physical building blocks at each level of organization. The ***principles of organization***, rather than the specific form in which they are found, are therefore the topics of central interest. For this reason, the general concepts and terminology of cybernetics are useful for discussion of "systemic organization" in a general sense and not tied to one or another specific example from the natural world.

II. A General Definition of Fitness

A. The Goal-Directed System of Cybernetics

Nearly 50 years ago, Norbert Wiener proposed several key concepts in his book, ***Cybernetics***. Among these was an outline of the so-called "goal-directed system", which has become a central paradigm of robotic design (see Figure 1).



Stability Function
(long-term
information
storage)

Flexibility Function
(1. short-term effects
2. perception of
relevant external
information)

Figure 1: The four components of the "goal-directed" system of cybernetics.

The goal-directed system contains four essential components: a sensor mechanism (i) for detecting changes in the environment, an effector (ii), or robot-arm, for effecting changes in the environment, and two control center elements: the error detector (iii) and the goal state (iv). The goal state is in essence a definition of the desired state which the robot would like to achieve in the external world. The error detector is the mechanism through which the current state of the external world, as detected by the sensor, is compared with the goal state. By determining the magnitude of the difference between the actual state and the ideal state, the error detector can then instruct the effector on what actions to take, thus reducing the difference between the actual and ideal states. The new state of the environment is then perceived, and comparison and action are repeated until the environmental state is sufficiently close to the ideal state that the goal-directed system can cease its manipulations.

This type of robotic function is entirely straight-forward for simple industrial tasks. In a more complex environment with multiple goals, the hierarchical control of the goal-directed system becomes much more complex. Not only must the robot carry out certain tasks in the external world, it must repeatedly take actions related to its own self-maintenance. The two control functions can be described as involving systemic stability and contact with the external world (systemic flexibility) (Figure 1).

The necessity of some kinds of sensory and motor mechanisms in a working robot is perhaps obvious, but there are several general principles of the control mechanism which deserve further emphasis: The first is the fact that the control mechanism consists of two main components, which must communicate with one another, but whose roles are fundamentally different. On the one hand, the "goal state" is concerned with the long-term preservation of essential systemic information. The "error detector," on the other hand, has the function of making contact with the external world - a role which involves both reception of environmental information and control of the effector mechanisms for making adjustments to the external situation. Despite the very different "internal" and "external" orientations of the control elements, they must "speak the same language". That is, the error detector must be able to understand the information concerning the ideal situation, as defined by the goal state, and then translate that information into commands appropriate for the control of the effector mechanisms.

The requirement that the two control elements deal at the same task level concerning the balance of the "ideal" and the "actual" states of the system means that, in terms of the hardware of computer systems: (i) the two control elements are generally the same kind of processor (identical, or at least similar, CPUs), and, as a consequence of their physical similarity, (ii) they can communicate over a parallel bus for rapid and simple information exchanges. What is essential for control of the system is that the information concerning the goal state and the intended manipulations of the actual state be encoded in a suitably efficient form in ***both*** control elements. Provided that they work with the same code, then the two control elements will be able to communicate with one another easily.

In contrast, for the information exchange from the sensor to the error detector or from the error detector to the effector, there is the necessity of signal transformation. Transformation is normally required when communicating between the control center and the external world, because the coding in the control center, whatever form it may take, will necessarily be a code which specifies in a highly simplified form the desired dynamics between the system and its external world. In general, the control center encoding will be a static representation in a lower number of dimensions than the higher dimensionality and greater complexity of the external world. The nature of signal transformation is easily seen in the control of the effector mechanism, in which a static description of the goal state must be translated into the sequence of robotic movements needed to achieve that state. For this purpose, the sequentialization of the control center information into a series of movements in three-dimensional space is essential. These issues of data representation and signal transformation are well known in robotic design, particularly the design and use of so-called "special purpose processors" which are used in sensor and effector mechanisms (Volk, 1985).

These very general principles of robot design can be summarized, as shown in Figure 2. They have evolved strictly within the confines of cybernetics, but they suggest a general definition of efficient systemic

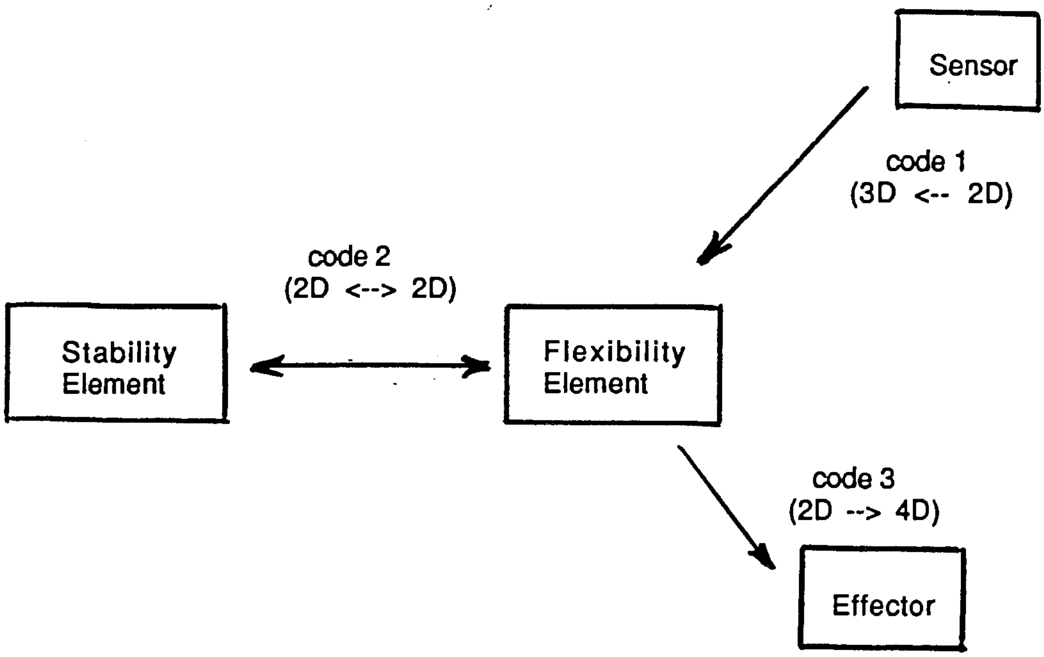


Figure 2: Basic insights concerning the goal-directed system architecture. There is dual control (master/slave configuration) for motor output and three separate internal languages. The sensor mechanism transforms environmental information from its given form into a form suitable for the control structures (Code 1). Control is exerted by "peer coprocessors", which communicate over a parallel bus (Code 2). External effects are obtained by transformation of the control code into motor operations (Code 3).

organization. Such a definition of "fitness" can be stated as follows:

> Viable systems require a balance between informational stability, on the one hand, and informational flexibility/usage, on the other hand. These somewhat contradictory tendencies can be put into approximate balance by having two equivalent control center components dedicated to their respective functions (a "stability element" and a "flexibility element"). Physical similarity between the control elements facilitates communication between them and allows them to store their information in mutually comprehensible form without signal transformation.

If the above definition of fitness has general validity - i.e., beyond the realm of robot design, then we would expect to see it realized in natural systems and, moreover, we would then have grounds for considering the implementation of such principles of fitness in other artificial systems. Let us see, therefore, how pervasive this definition of fitness is in the natural world.

B. The Central Dogma of Cell Biology

The living cell has two varieties of informational macromolecules, the nucleic acids (DNA and RNA) and protein. DNA is found predominantly in the cellular nucleus, where it produces RNA. RNA leaves the nucleus an produces protein in the cellular cytoplasm. A summary of the flow of control in the cellular system can be found in the so-called "central dogma" of molecular biology. That dogma indicates the channels of information flow among the nucleic acids and proteins, as well as the channels through which information does ***not*** flow (Figure 3).

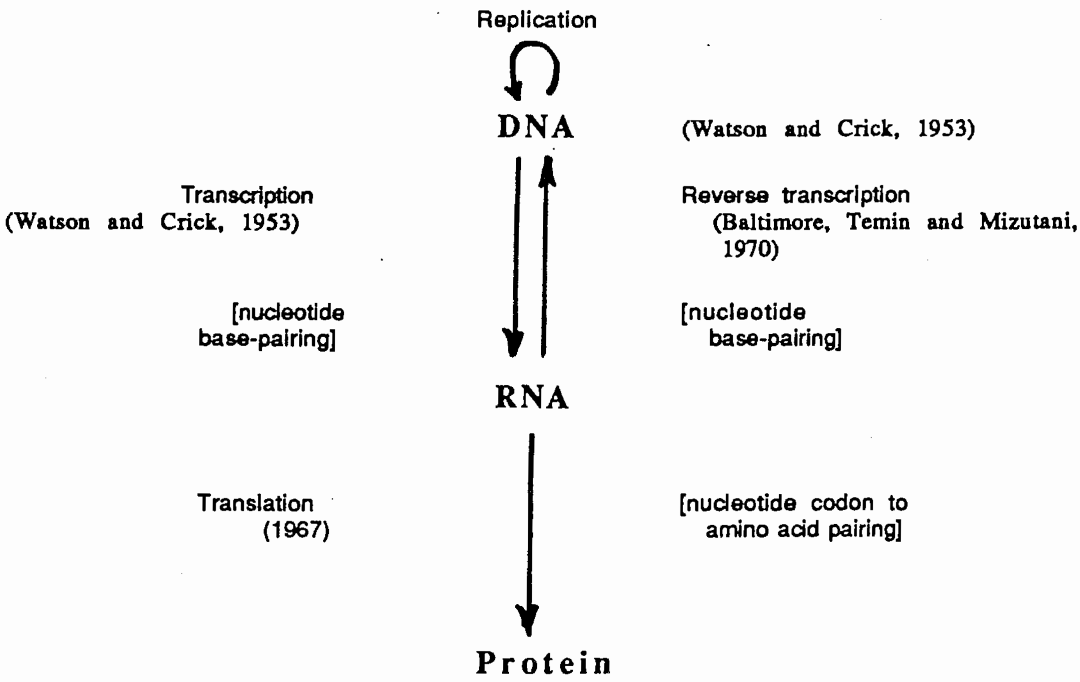


Figure 3: The central dogma of molecular biology. Note that the absence of information flow directly between DNA and protein.

DNA is known to be the molecular mechanism for storing inheritable genes. The sequence of the four nucleotide bases, adenine (A), guanine (G), cytosine (C) and thymine (T), in the DNA is the information which can be used for building all of the protein products of the cell. In order to construct protein, the DNA sequence is first transcribed into a complementary RNA sequence within the cellular nucleus. The RNA then leaves the nucleus and enters the cytoplasm where it directs protein synthesis. The essence of the code is that specific purines (TC) bind selectively with specific pyrimidines (AG). When a DNA double helix is partially unraveled to expose the interior of the helix, the exposed bases will bind only with the appropriate complementary bases. The newly synthesized RNA sequence can then be used to translate the original nucleic acid sequence into an amino acid sequence, by employing the so-called transfer RNA molecules. Amino acids, when bound together in chains, form peptides (which, in their normal 3D configuration are called proteins) and proteins are the essential work-horses of the cell. They include all of the enzymes which catalyze biochemical reactions in the cell, and are the essential structural molecules which give the cell its sensory and motor functions.

Because of the importance of the nucleic acid storage of the genetic information and its realization in the form of protein, it can be said that the nucleic acids and the proteins together constitute the essential ***informational core*** of all cellular life. The importance of these three types of molecule, DNA, RNA and protein, can be clearly understood from the following: If one were to know the entire DNA structure of a cell, one would know both the species it comes from and indeed the individual organism. If one also knew the RNA content of that cell, i.e., the segments of genetic information that are in repeated use for protein synthesis, one would know its differentiated state, i.e., what kind of cell it is - liver cell, neuron, blood cell, etc. Finally, if one also knew the protein content of the cell, one would know its precise level of metabolic activity. For example, knowledge of the nucleic acid content of a cell might tell us that it is a neuron from a monkey, but if one also knew the protein content, one could say that it is perhaps an inhibitory interneuron which secretes GABA at its synapses. In other words, knowing the nucleic acid and protein content, we would know the entire behavioral repertoire of the cell. We would know all that the cell is and can become. Similar statements cannot be made with regard to the many other types of other (essential, but informationally less-important) molecules, such as the carbohydrates, lipids and fatty acids.

C. The Central Dogma of Atomic Physics

Regardless of the mathematical difficulty of quantum mechanics, the atomic system is fairly simple because of the small number of constituent particles. The energetics of their interactions is complex, but the basic pathways of informationa flow can be expressed in a simple "central dogma" analogous to that for the cell (see Figure 4). This "dogma" is so fundamental to our understanding of the physical world and so far beyond dispute that it is normally stated simply as fact and not given further discussion. Nevertheless, the central dogma is a succinct statement of several of the most fundamental relationships known in physics.

As in the cellular system, there are three principal components (the nucleons [i.e., the protons and neutrons] and the electrons), the numbers of each of which is crucial for defining the properties of the given atom. As in the cell, there are many other components (particles involved in the interactions among nucleons and electrons), but their roles are of secondary importance.

The principal difference between the two kinds of nucleons concerns their net charge. Both weigh about 2000 times more than the electron, both are fermions with one half unit of angular momentum, and both have small magnetic moments due to the internal revolution of charge, but only the proton has a net (positive) charge. The neutron is comprised of a positive charge and a negative charge, which makes it neutral. This difference between protons and neutrons is crucial in determining their roles in the atomic system. Having a positive charge, the proton affects and is (weakly) affected by the charged electronic environment of its own electrons and those in the molecule where it lies. The neutron, on the other hand, is oblivious to such chemical phenomena and has no direct influence on them. It does, however, play an important role in securing atomic stability. That is, by means of its binding to both protons and neutrons in the nucleus through the nuclear force, the neutron holds many-proton nuclei together. Unlike the protons, which exert strongly repulsive forces on one another, the neutrons provide predominantly an attractive binding force and thus play a central role in nuclear (and therefore atomic) stability.

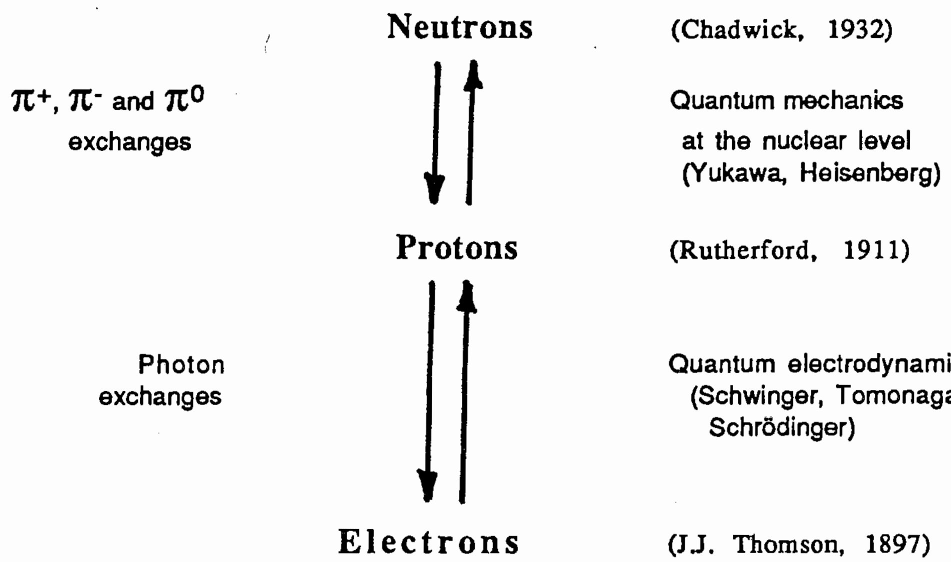


Figure 4: The central dogma of atomic physics. Note the absence of direct interactions between neutrons and electrons.

As was the case for the cell, knowledge of these three principal components of the atom is sufficient to tell us essentially all of the features of a given atom. If we know the number of protons, we know the element; if we know the number of neutrons as well, we know the isotope and therefore the stability/instability (half-life) of the nucleus. Finally, if we know the number of electrons that are present, we know the ion and the electrical state of the atom. Armed with this knowledge, we can predict the entire repertoire of functional (chemical) possibilities for the given atom. There are of course other particles present in atoms, notably the mesons which carry the nuclear force, and the photons which carry the electromagnetic force. These particles are also essential aspects of atomic physics, but the precise numbers of such particles are irrelevant for a first-order description of any atom. For this reason, the dynamics of the interactions among nucleons and electrons are the most important aspects of atomic structure.

D. Functional Isomorphism

Clearly, the structures involved in the living cell and the physical atom are very different, but there is a notable structural and functional similarity among their three principal components. No known laws of causality would predict that similar functional organizations would emerge at various levels, but it is conceivable that, through processes of "natural selection" at both the atomic and the cellular levels the need for both (i) systemic stability and yet (ii) contact with the external world has led to the emergence of similar principles of control. At both levels, the control duality embodies the contrary needs of maintaining the stability of the system's core information (electrical charge in the atom and genes in the cell) and flexibility (the ability to influence the external world (the electromagnetic environment for the atom and the biochemical environment for the cell).

E. The Central Dogma of Psychology

The simple restatement of well-known principles of natural organization in terms of "central dogmas" is of little value unless it predicts something new. If the dogmas in physics and biology have general validity beyond the specific systems involved - that is, if they embody general principles of cybernetic self-organization, then certainly a balance between stability and flexibility should be evident at higher levels in the biological world - and perhaps in social structures as well. In principle, various examples of dual control could have arisen, so there remains the task of examining higher-level systems for such structures.

Is there a similar principle of control at the next quantal level of natural organization, the multicellular organism? Unlike plant organisms, it is evident that animal organisms have distinct control centers in the form of central nervous systems and, moreover, the vast majority of animals have bilaterally symmetrical brains. The bilateral symmetry of the cerebral hemispheres in higher organisms, particularly mammals, means that there is indeed a kind of "dual control center", but there is little indication of functional differences between the left hemisphere (LH) and the right hemisphere (RH) in most animal species. In contrast, one of the outstanding neurological differences between Man and ape concerns the functional specialization of the human cerebral hemispheres. What then is the nature of the functional asymmetry in the human brain and does it reflect a similar dichotomy of "stability" and "flexibility"?

First of all, it is essential to consider the two aspects of human behavior which are most characteristically human. These are language and tool-usage. Neither is totally unprecedented in the animal world, but both are developed to such an extent in Man that similarities with other species are insignificant compared to their qualitative and quantitative differences. Language and tool usage lie at the heart of all human social organizations and preoccupy us nearly to the exclusion of activities which do not involve language and tools. Moreover, it is self-evident that, whenever we wish to have some influence on the external world, we exert that influence through language (written or spoken) and the manipulation of tools using predominantly the favored hand. In this respect, it can be seen that human neuropsychology also has a "central dogma" in so far as the expression of information is made through one of two similar "control structures" (Figure 5). Corballis (1992) has argued that the essence of LH capabilities, as related to both language and tool-usage, is the sequentialization of motor tasks. Although the RH experiences the same world as the LH, the RH lacks the fine motor control needed particularly for speech and writing.

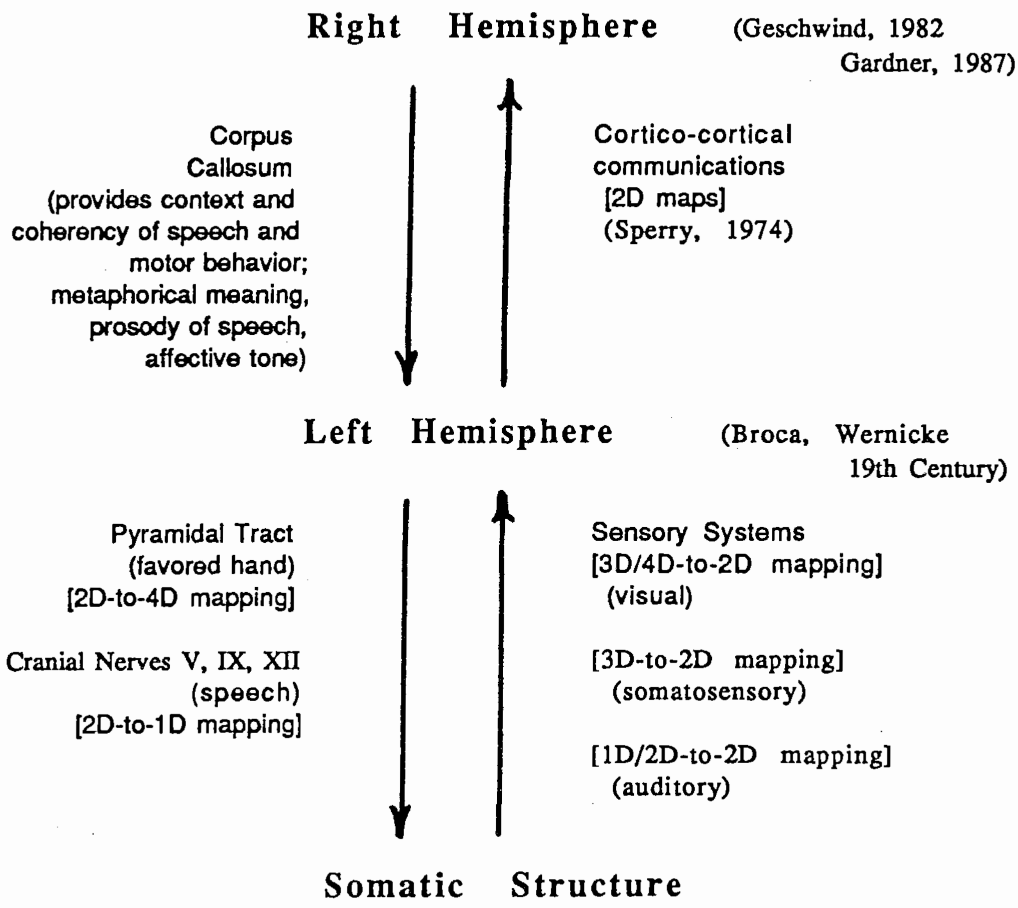


Figure 5: The "central dogma" of human neuropsychology

What remains unclear with regard to this central dogma are the functions of the right hemisphere and the nature of the communication between the hemispheres across the "parallel bus" called the corpus callosum.

1. The Role of the Cerebral Hemispheres

The two clearest examples of functional differences between the cerebral hemispheres are related to motor activity. Nearly 95% of all individuals (most right-handers and even a majority of left-handers) control speech output primarily from the left hemisphere. Of course, the bulk of the population is also right-handed, which means that most skilled motor activity (writing and tool-usage) is controlled from the LH. Moreover, in right-handers, even when the non-dominant hand is being used for skilled motor activity, there is considerable LH involvement, but the RH is not similarly involved in right-hand activity. These well-known facts from human neurology are truly remarkable, because they imply that the two quintessentially human behaviors, speech and tool-usage, are controlled by the LH.

It is not the case, however, that the RH is useless or uninvolved in language or in tool-usage. On the contrary, the RH plays an important role in both, but it is clearly ***not*** an executive role. That is, the RH does not have control over the effector mechanisms which are directly responsible for speech and the skilled motor control of the favored hand, but it does have an indirect influence and is important for a variety of high-level functions. Empirically, what is best known is that individuals who have suffered RH brain damage can still understand and produce language in a fairly normal way, but they show characteristic cognitive deficits which are not directly related to the mechanisms of motor output. Two findings are of principal interest.

a. The loss of "context" following right hemisphere damage

The effects of LH damage are relatively clear, particularly for language production: anterior LH damage will often reduce or eliminate speech production for long or short periods. Syntactic deficits for both speech production and understanding are clinically well-known. Posterior LH damage produces semantic deficits in both speech and understanding.

Linguistic Level	Lesion	Characteristic Findings
Word	RH	Loss of word connotations; reliance on denotations.
	C C	Paucity of affect words in spontaneous speech.
Phrase	RH	Inability to select caption for non-verbal cartoon. Inability to select punch-line for verbal jokes. Inability to understand metaphors.
	C C	Failure to appreciate metaphorical meanings.
Sentence	RH	Inability to construct sentence from list of words.
Paragraph	RH	Inability to construct coherent paragraph from list of sentences. Inability to detect anomalous facts in short narrative.
	C C	Tendency toward concreteness and details when meaning required.
Prosody	RH	Loss of affective expression. Loss of affective comprehension.
	C C	Spontaneous speech shows lack of affect or inappropriate affect.

Table 1: Language deficits following RH or callosal (CC) damage (from Cook, 1986)

For these reasons, the LH is referred to as language "dominant", but RH damage also leads to characteristic language deficits of a more subtle variety. Although RH-damaged patients can understand and produce speech, they have difficulties in understanding the higher-level implications of normal language. Typically, the understanding of metaphors and similes is impaired; the intent or gist of a segment of speech is not understood; and the "moral" of a story and the "funniness" of jokes are not appreciated. Although the phrase, story or joke may be ***literally*** understood and the patient capable of repeating it word-for-word, the implications which are obvious to normal subjects will be lost. Similarly, written or spoken language which is syntactically sound, but semantically anomalous may not be detected as anomalous. It is as though the cognitive "context" within which language decoding normally takes place is absent. Gardner et al. (1983) refer to this characteristic feature of RH-damage as "missing the point" - despite the fact that literal understanding is normal. These and related findings are summarized in Table 1.

b. The "confusional state"

Geschwind (1985) has argued that the ***most common*** disorder following RH damage encountered in the neurological clinic is the "confusional state." He distinguishes the RH confusional state from the deficits which are a consequence of diminished alertness following brainstem damage. Unlike the drowsiness or semicomatose behavior of such patients, in the confusional state following RH damage, patients are fully alert, even talkative, and can respond appropriately to most simple verbal inquiries. But these patients have difficulties in staying within the appropriate "context" of conversations, are easily distracted by irrelevant information, and are inadvertently "witty" by jumbling ideas and confusing facts. It is as though the contextual information which normally guides language production is missing in such patients. The eight principal features of the "confusional state" are listed in Table 2.

1. Loss of coherence
2. Paramnesia
3. Wild paraphasias and propagation of error
4. Occupational jargon
5. Inattention to environmental cues
6. Isolated disturbance of writing
7. Unconcern or denial of illness
8. Apparently playful behavior

Table 2: Eight features of the "confusional states" following RH damage (Geschwind (1982))

The significance of the confusional state is that it is a frequently-encountered ***psychological*** consequence of unilateral brain damage which has no effect directly on sensory or motor functions. The inability to understand or use language at all is perhaps a starker expression of the loss of characteristically human capabilities, but, with the basic language generating and receiving mechanisms of the LH intact, it is still possible to lose essential aspects of human cognition which distinguish us most clearly from other animal species.

The fact that the cerebral hemispheres show functional specialization for the high-level, symbolic tasks characteristic of Homo Sapiens indicates that the "dual control" of the bilateral nervous system is something more than the working of equivalent "coprocessors". One hemisphere, normally the left, is dominant for the executive control of the musculature involved in speech and skilled motor activity. The other hemisphere plays a role in providing the cognitive context within which the specific motor sequences must be carried out. When the LH is damaged, the ability to express and receive ***symbolic*** information is greatly reduced. When the RH is damaged, the LH is still capable of performing the necessary sequentialization of movements and the decoding of sequential signals, but the normal cognitive context of information processing is lost, and behavior becomes bizarre.

These well-established features of the hemispheric specialization in Man indicate a "central dogma" of human neuropsychology which has a structural and functional similarity to the dogmas of atomic physics and cell biology (Table 3).

	ATOM	CELL	MAN
Is there a Control Center?	nucleus	nucleus	brain
Is there Dual Control?	nucleons	nucleic acids	cerebral hemispheres
Internal Control Element	neutrons	DNA	right hemisphere
External Control Element	protons	RNA	left hemisphere
Preipheral Structure	electrons	protein	body

Table 3: The first three central dogmas of natural science

This isomorphism among the control dualities of the atom, cell and human organism indicate that the dominant physical, biological and psychological systems on Earth have embodied functionally-similar mechanisms of control. At all three levels, there has emerged a control duality, in which informationally-similar entities are specialized for functions ensuring informational stability, on the one hand, and informational expression, on the other hand. It might be argued that these similarities are nothing more than an analogy without implications for scientific research, but several clear predictions can be made concerning the mechanisms of information transfer in the respective systems. Before turning to such mechanisms, however, let us discuss two further topics which indicate the significance of the isomorphism among these systems - the disorders of control and emergent properties.

III. Disorders of Control and Emergent Properties

If the similarities among these diverse systems are truly significant for their control, then we should be able to identify what the system gains by having such control and, conversely, what the system loses when the control duality is lost.

A. Emergent Properties

1. Atomicity

The control duality in the atom makes it possible for a variety of different physical elements to exist. Without the neutron, the only atom would be hydrogen, and the only molecule would be H_2. There could then exist in the physical universe only a hydrogen plasma. By providing more nuclear "glue", neutrons allow for multi-proton nuclei to be held together, despite the strong repulsion among the protons' electrostatic charges, and this in turn allows for the stable existence of a variety of multi-charge atoms caapable of holding many electrons. In other words, the entire "atomicity" of the physical world is made possible by the proton-neutron control duality. The proton-neutron distinction is of course not a sufficient condition to allow for all of atomic and molecular dynamics, but it is apparently a necessary one.

2. Life

Biological structures which have ***not*** incorporated the DNA-RNA duality are known to exist in the form of the DNA and the RNA viruses. In terms of their basic constituents (nucleic acid core, some protein content, simple membrane cover), they are structurally similar to tiny cells, but they lack all of the functional properties which are normally found in living cells. Alone, they do not metabolize, cannot replicate and show no signs of motility. Only once a virus has entered a living (metabolizing) cell with functional DNA and RNA, can it show signs of life, but even then only by utilizing the ***living*** cell's functioning metabolic and enzymatic machinery. In other words, "life" is inextricably linked to the dual control of RNA and DNA. Again, it is not the case that the presence of both RNA and DNA is sufficient for life, but their presence is necessary for the long-term viability of a functioning cell. If, for example, the DNA core of a cell is artificially removed or naturally disposed of (as in red blood cells), the cell's longevity is greatly decreased.

Basic Biological Structures	Nucleic Acids	Metabolic Activity?	Self-Replication?	Motility?
Viruses	RNA *or* DNA	no	no	no
Bacteria	RNA *and* DNA	yes	yes	yes
Protista	RNA *and* DNA	yes	yes	yes
Fungi	RNA *and* DNA	yes	yes	yes
Plant Cells	RNA *and* DNA	yes	yes	yes
Animal Cells	RNA *and* DNA	yes	yes	yes

Table 4: Living biological systems fall into one of five classes. The viruses share some structural features of the living systems, but they do not show the characteristic signs of life.

3. Mind

There is little agreement on what is neurologically different about human beings relative to other Primates or mammals in general, but it is an empirical fact that we, as a species, show an unusually wide range of behaviors. This variety of behaviors is made possible by two of the unusual features of human existence, language and tools. Primitive means of communication and primitive tool-usage are in fact known in several species, but there is a huge jump to the complexity of human language and human tool-making and tool-usage relative to the languages and tools elsewhere in the animal world. It remains an unanswered question whether or not the skilled motor activity of tool-making and the complex world of symbolic languages requires hemispheric specialization, but it is an empirical fact that the two strongest examples of functional asymmetries in Man are specifically in those two realms. Without pursuing the philosophical problems of a proper definition of "mind", it can nonetheless be stated that those properties which are characteristically human and necessarily the central focus of most research on the questions of "homonization" are specifically those topics where the human brain shows unmistakable hemispheric specialization.

For this reason, Jaynes (1978) has traced the evolution of the human mind specifically in terms of changes in hemispheric relations. The first step, which coincided with the evolution of human symbolic speech and the emergence of tools, entails the development of functional asymmetries of the cerebral hemispheres. The second step, according to Jaynes, was the transition from the "bicameral mind" - characterized by auditory hallucinations ("the voices of the gods") - to the modern mind. The nature of the evolution of the Primate nervous system is controversial, but attempts to delineate the nature of the transition from Ape to Man necessarily focus on language and tool-use and their relation to the cerebral hemispheres.

B. Disorders of Control

In the most general sense, the universe does not care whether physical entities exist in one form or another. Individual systems, however, are by their nature self-preserving. This is particularly evident for biological and social systems whose entire existences seem to be devoted to self-perpetuation. Given that continued existence of the system as a system is, for the system itself, desirable, it is possible to identify states which lead to the destruction of the system and are therefore by definition undesirable. In other words, there are states of relative "health" and "unhealth" for any given system.

It can also be said that, purely from an anthropocentric point-of-view, much of modern scientific research concerns the disorders which can arise in natural systems. "Disorders" refer to any changes in the system which threaten its stability and longevity. The disorders of physical, biological and psychological systems therefore include an extremely broad range of topics, but it is relevant to the present essay on control structures to note what the principal classifications and dynamics of pathology are at these different levels.

1. Radioactivity

In the atom, the principal form of pathology entails the transformation of the nucleus and the emission of energy associated with the various forms of radioactivity. There are essentially two classes of radioactivity - those associated with proton excess and those associated with neutron excess. Either excess leads to a reconfiguration of the nucleus with the release of energy and a change of the atomic element. A neutron excess eventuates the transformation of a neutron into a proton, with the release of an electron and electromagnetic radiation (β^- decay). It is typically a low energy reaction. A proton excess, on the other hand, can be resolved in one of three ways: a low energy transformation of a proton into a neutron with the release of a positron and electromagnetic energy (β^+ decay); a higher energy transformation involving the release of helium nuclei (α particle decay); and/or a still higher energy transformation involving the break-up of the entire nucleus (fission). It is of some interest that the more drastic forms of atomic change are brought about by an excess of the externally-oriented control element, the protons, whereas the change brought about neutron excess involves merely the movement of an electron (within a neutron) to the peripheral electron shells. In both cases, the charge properties of the nucleus are changed, implying a change in the atom's electron environment and its chemical reactivity.

2. Cancer

There are a great many known disorders of cellular existence - most of which are associated with the pathologies induced by an excess or a deficiency of cellular nutrients. Therapy of such disorders is in principle straight-forward, in so far as the excess or deficiency can be dealt with directly. In contrast, the so-called neoplasms, or cancers, are unusual cellular diseases in being examples of the loss of the normal control over cellular reproduction. They are difficult to treat because they are systemic disorders that cannot be corrected by the simple addition or subtraction of one cellular component. Cancer involves excessive cell division and the further production of cancerous cells, often to the detriment of the organism as a whole. Not all cancers have been shown to have viral origins, but many have been proven (e.g., leukemia) and a great many more are suspected to have viral origins (e.g., AIDS). There are two fundamental types of such oncogenic cancers, those induced by RNA viruses and those induced by DNA viruses. The RNA type is malignant (leukemias, sarcomas, AIDS, etc.), whereas the DNA type is generally benign (for example, the wart viruses). In other words, there are two types of the loss of control at the cellular level - both involving abnormal cell differentiation. One is malignant, and requires the participation of an RNA cancer virus, and one is benign, involving DNA cancer viruses.

3. Psychosis

Mental disorders are traditionally classified into two major types in psychiatry: the psychoses and the neuroses. The physiological causes and consequences of the neuroses can be studied in animal models and, in human patients, the underlying psychological problems can be treated psychologically and sometimes cured using behavioral techniques. In contrast, the psychoses, which are subdivided into two main categories, schizophrenia and manic-depression, are not amenable to psychiatric treatment; there are no known animal models; and "treatment" is confined to the pharmacological suppression of symptoms, rather than cure. In other words, the psychoses are fundamental disorders of the human mind, without analogy in the animal kingdom.

It is therefore of interest that, unlike the neuroses, the psychoses exhibit lateralized functional abnormalities of the brain. The precise nature of the brain disorder in psychosis is in fact a highly controversial topic, but certain facts are established. Most importantly, a diagnosis of schizophrenia can be made only when certain of the so-called first-rank symptoms are present, namely the auditory hallucination of voices addressing the patient in the third person and when the patient exhibits incoherent verbal behavior, that is, the so-called schizophrenic "word salad". This is the apparently meaningless jumbling of words and phrases in the patient's spontaneous speech. These language disorders are associated with a variety of physiological abnormalities of the left hemisphere - including electrical and metabolic hyperactivity. In contrast, manic-depression (and particularly monopolar depression) is characterized by physiological hyperactivity of the right hemisphere (Table 5).

Schizophrenia	Affective Disorders
Left temporal dysfunction	Right temporal dysfunction (in depression, not mania)
Left temporal lesions associated with schizoid behavior	Right hemisphere lesions associated with affective disorders
Association between dominant hemisphere temporal epilepsy, schizophrenia and paranoia	Association between non-dominant hemisphere temporal epilepsy, manic-depressive psychoses and dysphoric states.
Psychopathy linked with left hemisphere fronto-temporal dysfunction	Depression linked with right hemisphere frontotemporal dysfunction
Left hemispheric stability of visual evoked potentials in schizophrenia	Higher visual evoked potentials in the right than left hemisphere in psychotic depression

Table 5: Hemispheric abnormalities in the psychoses (after Flor-Henry (1983) and Gruzelier (1979, 1985)

The most revealing fact indicating the importance of RH pathology in depression is that unilateral electroconvulsive shock therapy delivered to the RH is as effective as bilateral therapy and unilateral LH therapy is ineffective in relieving the symptoms of depression. The psychoses are quintessentially ***human*** mental disorders and, unlike the minor disorders of neurosis, they are associated with asymmetrical brain pathology. Schizophrenia is by far the more disruptive disorder (to both self and society), whereas depression has less malignant effects. Both, however, are psychological disorders which, to one degree or another, incapacitate the individual and prevent him from full participation in human society.

The emergent properties and disorders of control in the atom, cell and human organism are summarized in Table 6.

SYSTEM	Internally oriented control element	Externally oriented control element	Emergent property	Disease	
				Excess or hyperactivity of:	
				internal control	external control
ATOM	neutron	proton	atomicity	radioactivity	
				beta$^-$ decay	beta$^+$ decay alpha decay fission
CELL	DNA	RNA	life	neoplastic growth	
				benign growths (DNA-virus induced)	malignant tumors (RNA-virus induced)
MAN	right hemisphere	left hemisphere	mind	psychosis	
				manic-depression	schizophrenia

Table 6: Emergent properties and the pathology of control in natural systems

IV. The Codes of Nature

At this point, we have what is at least a curious analogy among the dominant natural systems on Earth. There is a structural aspect, in so far as similar but distinct control components are involved in the main functions of stability and flexibility. There is a functional aspect, in so far as one of the two control elements is concerned with "internal" information maintenance and one is concerned with "external" contact using that information. There is an evolutionary aspect, in so far as the functional duality at each level appears to give the respective systems remarkable emergent properties which are not found in other comparable systems which lack the control duality. Finally, there is a pathological aspect, in so far as disorders of either control element lead to characteristic diseases of the system: a more malignant disease when the "external" control element is involved.

These structural and functional similarities among very different systems suggest that there may be similar principles of systemic organization embodied in them, but what has not yet been addressed is the actual mechanisms involved in the flow and usage of the relevant information. Clearly, unlike the above "philosophical" discussion of emergent properties and systemic disorders, it is with regard to ***mechanisms*** that issues of empirical science arise. In other words, even if we have an isomorphism among these different systems, is there anything new that we can explain or predict? To answer this question, we must come down from the high tower of scientific "dogma" and discuss the known "codes" of information transfer at the various levels of natural organization.

A. The Atomic Code

The interactions of the fundamental particles of atomic physics are well-described using the formalism known as quantum mechanics. It is the "atomic code" in so far as it specifies all possible particle relations. The conceptual implications of quantum mechanics concerning causality and the wave/particle duality are complex and controversial, but the basic principles are easily understood. That is, the energy states in which a particle can exist are defined by the Schrödinger equation:

$$\Psi_{n,l,m}(r) = R_{n,l}(r) \cdot Y_{l,m}(\theta,\phi)$$

The indices n, l and m are integer quantum numbers which specify the energy substates of the particle. r, θ, and ϕ specify the location of the particle in the polar coordinate system. Given that each allowed combination of the quantum numbers, n, l and m, can be occupied by one spin-up and one spin-down particle, the entire set of allowed electron states can be tabulated (Table 7).

The energy states of nucleons are also governed by the Schrödinger equation, with suitable changes due to the smaller scale of the nucleus and changes due to the fact that there are two types of nucleon, protons and neutrons, but only one kind of electron. These differences imply some differences in the occupation numbers in the allowed states, but there is a general similarity of nuclear and electron structure (Table 7).

Of interest in the present context is that the Schrödinger equation has two main implications. The first is that there is a specific geometry of the allowed energy state for any particle (determined by r, θ, and ϕ). Secondly, the interactions of particles necessarily involves transitions from one distinct quantal state to another (determined by quantum numbers n, l, and m).

The focus of the present discussion has been on the nature of the control structures in natural systems, so let us look more closely at the mechanism underlying the known interaction between protons and neutrons. Most importantly, protons and neutrons exchange charged mesons, which leads to the transformation of protons into neutrons and vice versa. As illustrated in Figure 6, this interaction involves two main effects. The transfer of the basic information of the atomic system (i.e., electrostatic charge) means that the fundamental charge properties of the interacting particles are reversed.

	K	L				M									N															
n	1	2				3									4															
l	0	0	1 p			0	1 p			2 d					0	1 p			2 d					3 f						
m	0	0	-1	0	+1	0	-1	0	+1	-2	-1	0	+1	+2	0	-1	0	+1	-2	-1	0	+1	+2	-3	-2	-1	0	+1	+2	+3
	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓
	K	L_1	L_2			M_1	M_2			M_3					N_1	N_2			N_3					N_4						

	N							$J = \lvert l \pm s \rvert$							M							S		
	0	1	2	3	4	5	6	1/2	3/2	5/2	7/2	9/2	11/2	13/2	1/2	3/2	5/2	7/2	9/2	11/2	13/2	↑	↓	total
number of nucleons with each eigenvalue	2							2							2							1	1	2
		6							4						2	2						2	2	6
								2							2							1	1	8
										6					2	2	2					3	3	14
			12						4						2	2						2	2	18
								2							2							1	1	20
											8				2	2	2	2				4	4	28
				20						6					2	2	2					3	3	34
									4						2	2						2	2	38
								2							2							1	1	40
												10			2	2	2	2	2			5	5	50
											8				2	2	2	2				4	4	58
					30					6					2	2	2					3	3	64
									4						2	2						2	2	68
								2							2							1	1	70
													12		2	2	2	2	2	2		6	6	82
												10			2	2	2	2	2			5	5	92
						42					8				2	2	2	2				4	4	100
										6					2	2	2					3	3	106
									4						2	2						2	2	110
								2							2							1	1	112
														14	2	2	2	2	2	2	2	7	7	126
													12		2	2	2	2	2	2		6	6	138
												10			2	2	2	2	2			5	5	148
							56				8				2	2	2	2				4	4	156
										6					2	2	2					3	3	162
									4						2	2						2	2	166
								2							2							1	1	168

Table 7: Possible states of electrons (above) and nucleons (below) as determined by the allowed quantum numbers.

As a consequence of the need to preserve parity, both particles also reverse their spin properties (Figure 6). Because a nucleon is a particle with properties arising from the movement of its mass and its charge, nucleon-nucleon communication can be said to involve the reversal of both fundamental properties. These are well-known and established facts of nuclear physics, although the implications of proton-neutron interactions for nuclear structure theory are more controversial (Cook, 1987; 1991).

B. The Genetic Code

There are two main parts to the genetic code - the information transfer between DNA and RNA and that between RNA and protein. The DNA-RNA interaction is of interest because it is the way in which control center information, "genes", are exported from the cellular nucleus. A double-helical DNA molecule unwinds to expose the purine and pyrimidine bases in its interior and, with the help of RNA synthesis enzymes, a complementary RNA molecule is constructed. Interestingly, the DNA to RNA information transfer entails a double transformation of the original message. As shown in Figure 7, the base-pairing of purines and pyrimidines means that a purine in the DNA corresponds to a pyrimidine in the RNA. Moreover, there is a directionality to the one dimensional nucleic acid sequences, so that the start (3' end) of the DNA corresponds to the end (5' end) of the RNA. In other words, in the transfer of information between the nucleic acids, one unidirectional binary (purine/pyrimidine) sequence is reversed in both of the ways that are physically possible (Cook, 1984).

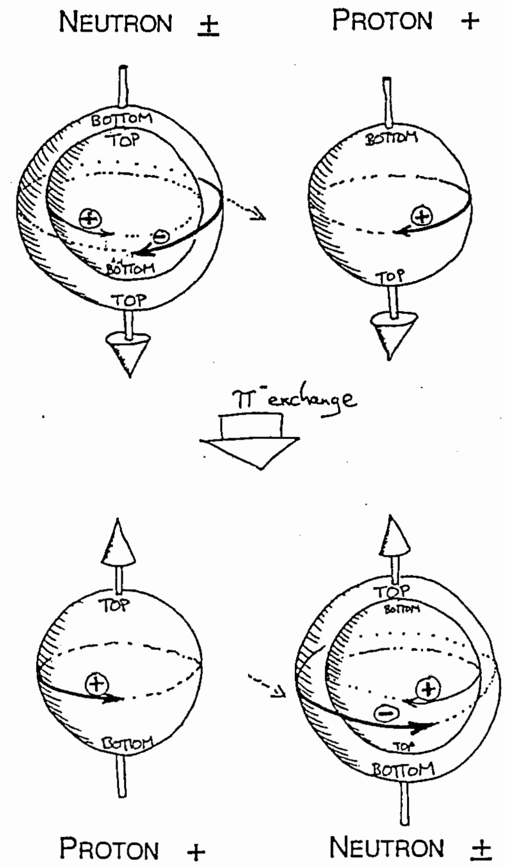


Figure 6: The double inversion of information in the neutron-proton interaction.

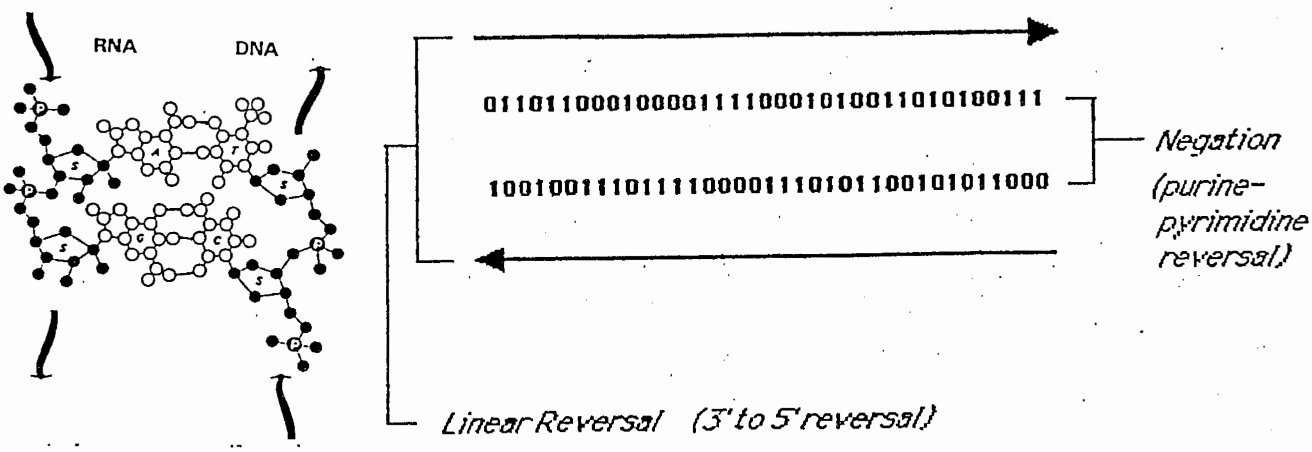


Figure 7: The double inversion of genetic information during nucleic acid interactions. The complementarity of base-pairing implies that the purine/pyrimidine binary code will produce its mirror-image. The linearity of the nucleic acids means that the mirror-image pattern is also front-to-back reversed as well.

C. The Cognitive Code

Unlike the atomic code (quantum mechanics) and the genetic code, many unanswered questions remain concerning what might be called the "cognitive code". There are several distinct areas of brain activity where we might ask questions about the underlying "code" used for information storage and transfer. These include the various sensory systems (most importantly, the reception and storage of visual, auditory and somatosensory information) and the motor systems; they are the focus of much interesting research at ATR and elsewhere (Figure 8). But let us focus on the question of the communication between the cerebral hemispheres and their possible relation to the mechanisms of information transfer in other natural systems.

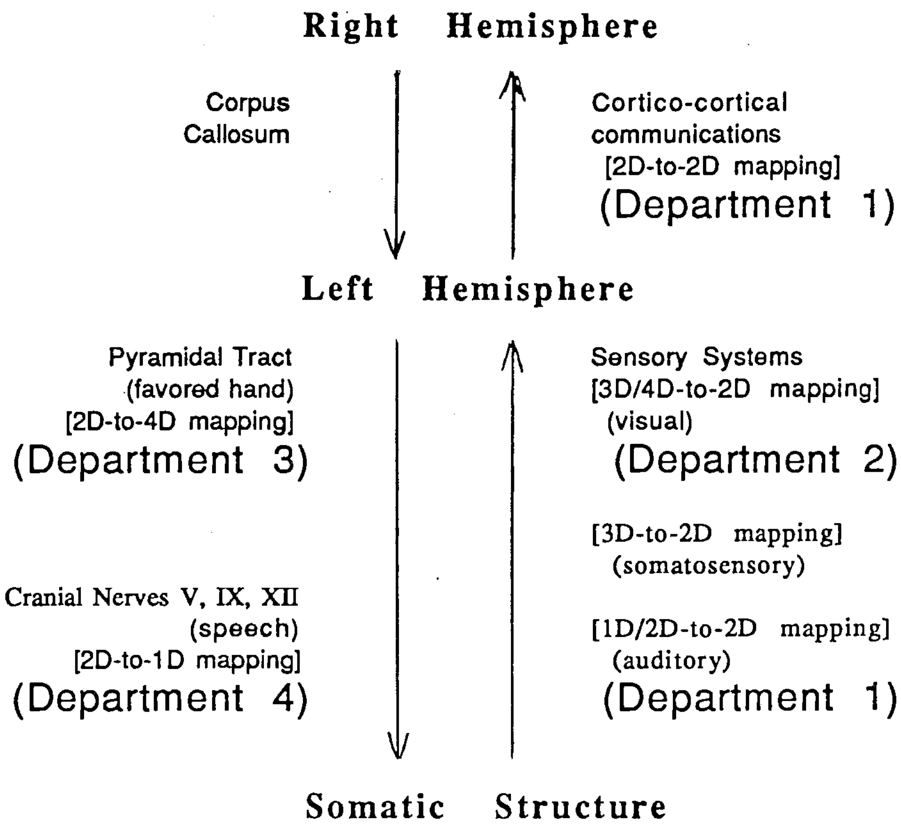


Figure 8: Elucidation of the "cognitive code" will require an understanding of several distinct codes used by the nervous system. Some of the major areas of research by the Human Information Processing Laboratories (ATR) in relation to the "central dogma" of psychology are noted by Department numbers.

First, some general findings from anatomy and physiology need to be reviewed. Mammalian nervous systems show approximate bilateral symmetry. There are no cortical structures which exist unilaterally and, although there are some differences in absolute size, no microscopic differences between the hemispheres are known which could explain functional differences.

Moreover, all sensory pathways show approximate bilateral symmetry, implying that the sensory experiences of the two hemispheres are identical. While small physiological asymmetries have been the focus of much research, it is worth emphasizing that all physiological studies (measuring electrical activity, glucose metabolism or oxygen consumption) have consistently shown an over-riding pattern of ***bilateral*** cerebral activation. Auditory stimulation produces bilateral activity of the temporal cortex; speech tasks produce bilateral frontal activity; etc. Physiological asymmetries related to lanaguage and handedness are of course known, but they occur within the context of bilateral activation - indicating quite explicitly that both hemispheres are involved in all normal motor and sensory processing. This fact of anatomical and physiological bilateral symmetry means that, whatever functional differences may exist, there are no scientific grounds for arguing that one task is performed by one hemisphere or the other, while the other hemisphere is simply "disengaged."

A second fundamental aspect of the organization of particularly the human brain concerns interhemispheric communications. The cerebral cortices are connected by a massive nerve tract, the corpus callosum. It is the largest nerve tract in the human brain and is approximately 15 times larger than the pyramidal tract (which carries information from the brain to the musculature for motor control). There are about 200 million nerve fibers in the corpus callosum. In fact, the distribution of callosal fibers is not uniform over the cortex, but there are enough fibers that each cortical column can send and receive callosal fibers to its contralateral homologue. What this implies is that, whatever the actual mechanism of cortical information storage, the activity in one cerebral cortex is tightly coupled to the activity in the other cortex. The basic anatomy of the corpus callosum is summarized in Figure 9.

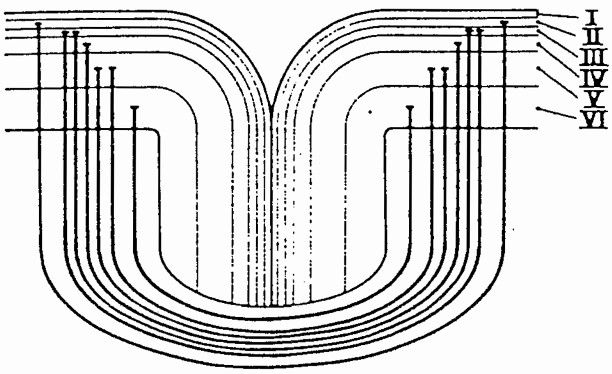


Figure 9: Callosal anatomy. Most callosal fibers are "homotopic", connecting homologous cortical columns in both hemispheres.

Finally, let us consider one basic issue in neuronal physiology. When a two-dimensional sheet of neurons (retina or cortex) is stimulated, it typically shows a two-dimensional pattern of both excitation and inhibition. This is normally represented using a so-called Mexican hat function, in which both the excitatory and inhibitory parts are defined as:

$$y = \pm b * e^{(-(a * x)^2)}$$

The constant a determines the amplitude of the effect, and b determines its lateral range. As shown in Figure 10, the Mexican hat is in fact the summation of a two gaussian-shaped regions of excitatory and inhibitory effects.

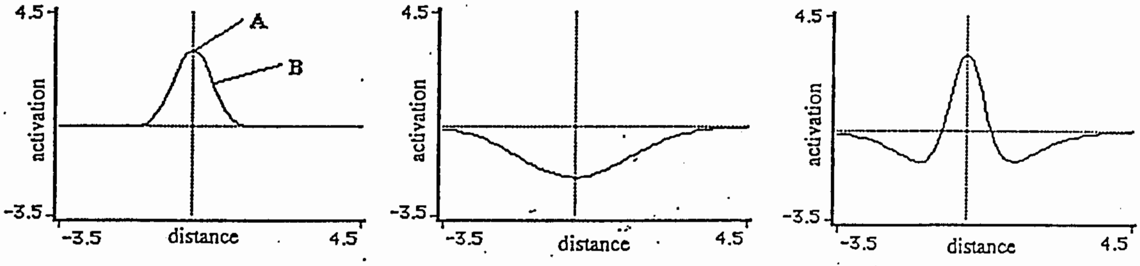


Figure 10: The summation of excitatory and inhibitory gaussians produces a Mexican hat (the precise shape of which depends upon the strength, a, and range, b, of the excitatory and inhibitory effects).

What is of particular interest is that, if we assume that a portion of cerebral cortex receives momentary stimulation of the Mexican hat type, then, given the homotopic anatomy of callosal fibers, it can have only a small number of possible effects on the contralateral cortex (depending only on the strength and range of inhibition or excitation). These can be summarized as: (i) a diffuse excitatory effect, (ii) a diffuse inhibitory effect, (iii) a focal excitatory effect, and (iv) a focal inhibitory effect. Interestingly, all four possibilities have previously been defended as mechanisms of interhemispheric communication (Table 8).

	Net excitatory effects	*Net inhibitory effects*
Topographical effects of callosal fibers (as a consequence, the configuration of callosal termination is informational)	Sperry (1962) Gazzaniga (1970) Gazzaniga and LeDoux (1978) Berlucchi (1983)	Kinsbourne (1974, 1982) Doty *et al.* (1973, 1977, 1979) Cook (1984a, b, c)
Diffuse effects of callosal fibers (as a consequence, the configuration of callosal termination is non-informational, i.e. modulating contralateral arousal)	Guiard (1980)	Dimond (1977) Galin (1977) Denenberg (1980, 1981, 1983)

Table 8: The four main hypotheses of callosal function.

There are indeed grounds for arguing that all four mechanisms may work at different regions of the cortex or in different species, but the fourth possibility, focal inhibition, is of particular interest for two reasons. It provides a mechanism for producing ***complementary*** patterns of hemispheric activation. The complementarity means that both hemispheres are actively processing information, and yet they are not needlessly duplicating the same processing. Depending upon the strength and width of the inhibitory effects, callosal inhibition can lead to (i) a focus of activation in one hemisphere and (ii) a surround of activation in the other hemisphere. In other words, this could be the mechanism by which one hemisphere holds a specific motor engram, while the other hemisphere holds the related context (Figure 11).

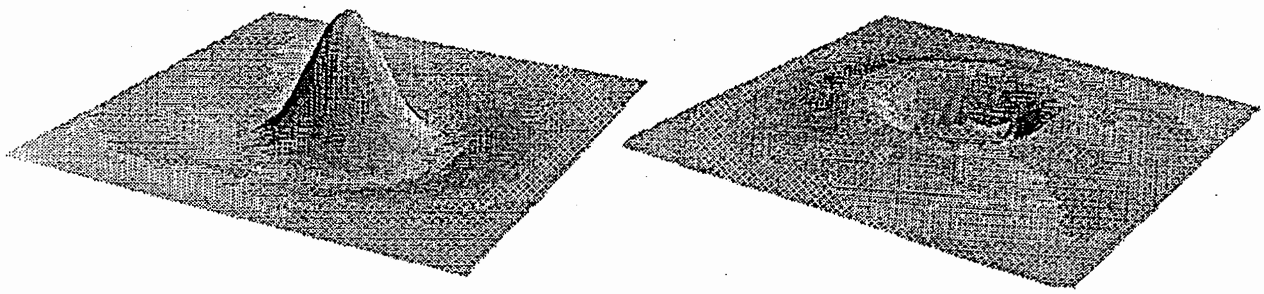


Figure 11: A focus of activity in the LH and a pattern of surround activity in the RH produced by callosal inhibition. Callosal inhibition is proposed as the mechanism underlying the known contextual functions of the RH.

It is also of interest that callosal inhibition implies the double inversion of the pattern of cortical activity (Figure 12).

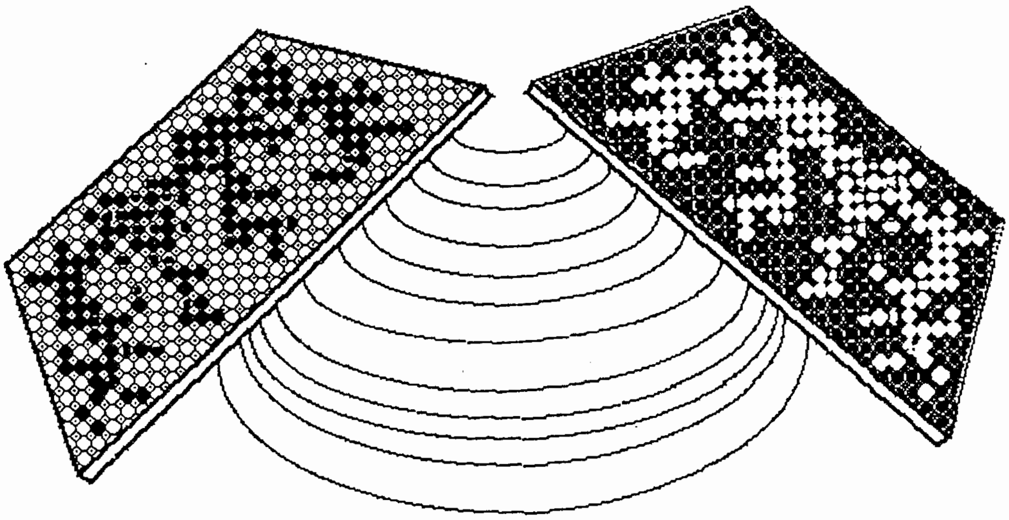


Figure 12: The double inversion of cortical information across an inhibitory, homotopic corpus callosum. Regions of activity on one side are inactive on the other side, and the entire pattern is mirror-reversed.

In comparison with the mechanisms of sensory input or motor output, questions of callosal communications may seem unimportant, but their significance lies in (i) their psychological importance (as demonstrated by clinical patients with RH or callosal damage) and (ii) their anatomical and physiological simplicity. It is worth recalling that elucidation of the genetic code was made possible by first clarifying the nature of nucleic acid interactions, and only subsequently was the more complex process of protein synthesis unravelled. In the same way, callosal information transfer is relatively simple in so far as callosal connections are homotopic and physiological activation is bilaterally symmetrical.

V. Conclusions

The purpose of this review of 20th Century science has been to illustrate a curious similarity of control in several important natural systems on Earth. Whether or not it is possible to prove logically that different systems are functionally "isomorphic" and guided by similar principles of self-organization is a philosophical question without a clear answer, but the practical question can be stated quite simply. In the design of artificial systems, should we try to borrow principles of design from other, relatively well-understood systems which are necessarily very different in terms of their actual structures? Analogies are often of limited value or simply misleading, and yet the search for general principles in nature is at the heart of the scientific endeavor. Given the extent of the similarities among the control structures in these systems, and given the fact that they involve the predominant physical, biological and psychological systems on Earth, it may be that the "isomorphism" reflects some general principles of systemic design that can be further exploited in the conscious design of man-made systems. What the "isomorphism" discussed above suggests is that artificial systems (at whatever level of physical organization) should embody principles of informational stability and informational flexibility. In the predominant systems on Earth, a balance between these two tendencies has been achieved by the functional specialization of structurally similar, informationally equivalent entities to perform quite different tasks. One is concerned principally with "internal control" - the maintenance of system information; the other is concerned with "external control" and contact with the surrounding environment. This is a principle of systemic control which can be readily exploited in artificial systems - whether robotic systems or human social systems (Table 9).

The balance of stability and flexibility functions in natural systems indicates a generality of the architectural principles of the goal-directed system (Figure 4) which simply could not have been appreciated in 1949. The use of dual control elements specialized for informational "maintenance" and informational "utilization" may be a prerequisite to the success of artificial systems which need to exhibit stability over time and yet allow continual informational give-and-take with their environments.

Level of Organization	Is there a dual Control Center?	Academic Discipline	Central Dogma?	Emergent Property
subatomic particles	no	particle physics	no	
atom	YES	atomic physics	YES	"atomicity"
	no	solid state physics	no	
molecule	no	chemistry	no	
	no	biochemistry	no	
cell	YES	molecular biology	YES	"life"
tissue	no	histology	no	
plant organism	no	botany	no	
animal organism	YES	zoology	no	
human organism	YES	psychology	YES	"mind"
SOCIAL SYSTEMS				
human family	(YES)	sociology		
business organizations	(YES)	business administration		
nation states	(YES)	political theory		
ARTIFICIAL SYSTEMS				
intelligent machines	(YES)	robotics	(YES)	???

Table 9: Control dualities are found in certain of the predominant systems on Earth. There is some indication of the advantages of control dualities in social and robotic systems, but such systems can in any case be designed to have characteristics which we, as the designers of the systems, want them to embody.

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