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Control Structures in Natural Systems: The Foundations for a Theory of Organizational Control

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ABSTRACT

We review the most basic, established facts from atomic physics, cellular biology and human psychology in order to identify the principles of systemic control known from the natural sciences. What we find is a structural and functional dichotomy of control in the atom, cell and human organism. In each of these systems, one of two nearly-identical control elements is specialized for the long-term stability of the system, the other is specialized for the short-term interaction with the system's immediate periphery. In light of the evolutionary success of these systems at their respective levels of organization, we advocate the establishment of artificial systems (computer systems, organizational systems, and large-scale social systems) that embody similar design principles.

Keywords: natural science, system science, control dichotomy, isomorphism

1. INTRODUCTION

Norbert Wiener's early work (1949) was motivated by the desire to design engineering systems on the basis of what was known from the natural sciences [1]. As important as his ideas have proven to be, the science that he studied in the establishment of the field known as cybernetics was, from our perspective today, quite primitive. The structure of the atom was known, but none of the basic insights of molecular biology or neuroscience were available for study. The cellular and brain sciences since the middle of the last Century have progressed significantly, and provide a great deal more detail about actual mechanisms than was available in the 1940s. In the present article, we review the "central dogmas" that have been established in the natural sciences, and show that a simple design principle is employed universally at the level of physical, biological and psychological organization. In light of those established facts about the structure and function of nature's most successful systems, the general principles of system design can be deduced, and applied to the construction of artificial and social systems.

2. NATURAL SCIENCE

Science begins with the secular belief that there is an objective world "out there" that we human beings, despite our various preconceived notions and stubborn beliefs in religious mythology, are trying to understand. To date, the most powerful and most coherent view of this material world is based on the scientific method – hypothesis creation, empirical testing and incessant skepticism. Mistakes have been made – and there are undoubtedly more to come – but genuine progress has also been made. While answers to the most difficult, metaphysical questions remain elusive, modern natural science has established a few hard core truths about the material world that have deep implications for human existence. Specifically, the basic facts of atomic physics, cellular biology and human neuropsychology can be stated succinctly as the three "central dogmas" of modern science (see Table 1) (see references [2]-[7] for further discussion).

Table 1: The Three Central Dogmas of Natural Science

System	The Atom	The Cell	The Human Organism
Control Center	Neutrons	DNA	Right Hemisphere
Dichotomy	↑ ↓ Protons	↑ ↓ RNA	↑ ↓ Left Hemisphere
Periphery	↓ Electrons	↓ Proteins	↓ Body

Table 1 shows the main components of the three most important systems in the physical, biological and psychological domains. Many other systems are known, but these three that dominate their domains, show "emergent properties" and participate in still higher-level systems.

The arrows in the Table indicate the dominant pathways of interaction of the components within the various systems. Within the respective control centers (the atomic nucleus, the cellular nucleus and the brain), there are complex interactions between and within the control center elements, but it is noteworthy that only one of the two control elements has significant contact with the system's peripheral structure. This control "asymmetry"

is the essence of the division of labor that is used in the control of these three systems.

It is of course clear that the material components and the nature of the dynamics within these systems are very different, but it is a remarkable fact that, by means of diverse evolutionary mechanisms acting at physical, biological and psychological levels, the overwhelmingly dominant systems in the physical, biological and psychological realms have isomorphic structures. Of the two control elements, one is “dominant” for executive control of the system’s peripheral structure and contact with the external world. In spite of this executive “dominance”, it is the other control center element that is responsible for the long-term stability of the system, and the system’s ability to exist as an integrated, coherent system in spite of disruptive influences from the environment.

The details of the mechanisms of interaction in each of these systems are what interest most scientists (quantum mechanics in atomic physics, the genetic code in cell biology, and the neuron code in brain science), but already at the level of “central dogma” there are significant lessons to be drawn for the organizational sciences. Specifically, the most successful systems (at least in the material conditions present on Earth) exhibit dichotomous control centers. At each level, the two control components are structurally virtually identical and contain roughly equivalent information, but they have different functional roles in the control of the respective system, thus allowing these systems to achieve both long-term stability, but also short-term effectiveness.

2.1. Atomic Physics

Structurally, the atom consists of a central, positively-charged nucleus (containing neutrons and protons) and peripheral, negatively-charged electrons. The allowed energy states of the nucleons and electrons can be described in detail with the Schrödinger equation, which is the essence of quantum mechanics. That much is the indisputable, established heart of both atomic and nuclear physics, but there are several principles of design that are worth studying before considering issues of mechanism. That is, every atom with more than one proton in its nucleus also contains neutrons in approximately equal numbers. The main difference between the two types of nucleon is that the proton has a net positive charge and, as a consequence, participates in a direct interaction with the peripherally-orbiting electrons, whereas neutrons are neutral and interact only with protons and neutrons within the nucleus. The

“central dogma” of atomic physics can therefore be stated as follows:

Neutrons \Leftrightarrow Protons \Rightarrow Electrons

where the arrows indicate direct interactions between the particles. Neutron-to-neutron, proton-to-proton and electron-to-electron interactions are also known, but the interaction between neutrons and electrons is negligible. In other words, the role of the neutron is *not* to maintain its electron periphery, but to facilitate nuclear stability. The positive charges of protons are generally disruptive of nuclear stability, but allow for the nucleus to interact with the peripheral negative charges of the electrons. Although primitive hydrogen atoms without neutrons are known, atomic systems capable of existing in various excited states, while retaining their characteristic atomic properties, require the presence of all three types of fundamental particle.

2.2. Cell Biology

The molecular biology of the cell was discovered in the latter half of the 20th Century and has led to a rather complete understanding of the mechanisms of the storage, activation, modification and flow of genetic information in the cell. While many details remain to be established, already the core facts about the flow of information in *every known* type of living cell can be summarized in the so-called “central dogma” of molecular biology:

DNA \Leftrightarrow RNA \Rightarrow Proteins

where the arrows indicate the flow of genetic information from one type of molecule to another. DNA-to-DNA and RNA-to-RNA information flows also occur, but the flow of information from protein to either of the nucleic acids does not occur. The meaning of the central dogma for the control mechanisms of living cells is straight-forward. Genetic information is stored in the form of DNA molecules, but, for the construction of proteins, the DNA information is transcribed into RNA molecules, which actually guide protein production. The essential division of labor here is the separation of long-term genetic storage (DNA) and short-term utilization (RNA). As a rule, the DNA information must be maintained intact for the lifetime of the cell, whereas the RNA information can be used to construct proteins for immediate effects in the cellular cytoplasm and there, in the cytoplasm, the RNA may be digested and the genetic information it contains destroyed. Loss of RNA is not fatal for the cell provided that more RNA molecules can be constructed using the DNA template protected in the cellular nucleus. Proteins, on the other

hand, are the work-horses of the cell, and are constructed, used and disposed of as necessary. In contrast to living cells, viruses contain either DNA or RNA, but not both and are metabolically inert until they enter living cells. *All* living cells contain both DNA and RNA. It seems that the emergent property of “life” is a consequence of this high-level division of labor – allowing the cellular system to be more than simple a container of biochemical reactivity, but rather becoming a self-sustaining system capable of ongoing metabolism and self-reproduction.

2.3. Human Psychology

The highest level anatomical division of nearly all animal nervous systems is between the left and right halves. In mammals, the cerebrum consists of the left and right cerebral hemispheres, and in human beings the functions of the left and right hemispheres are notably different. In man it is indisputably the case that the left hemisphere is dominant for the fine motor control needed for tool-usage (handedness) and language (particularly speech), while the right hemisphere is specialized for various contextual functions. As a consequence, the highest-level flow-chart of neuronal information in man, the “central dogma” of human neuropsychology [3, 4] can be summarized as:

Right Hemisphere \Leftrightarrow Left Hemisphere \Rightarrow Body

where the arrows indicate that information is exchanged between the left and right hemispheres across the corpus callosum (the largest nerve tract in the human brain), and from the left hemisphere to the body for skilled motor activity (predominantly, the speech organs and the favored hand). That is, although the nervous system is anatomically symmetrical, *characteristically-human* motor behavior (speech and tool-usage) is controlled by the left hemisphere (down the spine via the pyramidal tract). The flow of information that is notably lacking here is that from the right hemisphere to the body: the right hemisphere is *not* a competent executor for fine motor control. Although its contextual contribution to the executive functions of the left hemisphere is well-established and essential to keep the executive motor functions of the left hemisphere working within the proper cognitive framework, on its own the right hemisphere lacks the essential coordination to perform normal speech or control of the dominant hand. This division of labor between the left and right is intimately related to all of the quintessentially human forms of behavior (language, tool-usage and music) and notably absent in other species.

Much more is known concerning the structure and function of the human brain, but it is certain that the highest level division of labor between motor control, on the one hand, and conceptual stability, on the other, underlies the remarkable capabilities of the human mind. Other species lack these behaviors and also show only rudimentary signs of hemispheric specialization, suggesting that the emergence of “mind” from neuronal systems requires this type of functional specialization.

The reality of control dualities in natural systems is beyond dispute, suggesting that the process of evolution through natural selection favors systems with such control structures. A question of interest is therefore whether or not a similar control dichotomy can or should be implemented in artificial and social systems, where we collectively have the ability to decide upon organizational structures and upon the flow of information. Let us look briefly at several such systems to determine what types of control structures have thus far proven predominant.

3. APPLICATION TO ROBOTIC SYSTEMS

The robotics story is fairly straight-forward and dates back to the early days of cybernetics when the first tentative ideas about the design of “autonomous machines” were aired. On the basis of his study of natural systems in 1949, Wiener [1] proposed the so-called “goal-directed system”, as follows:

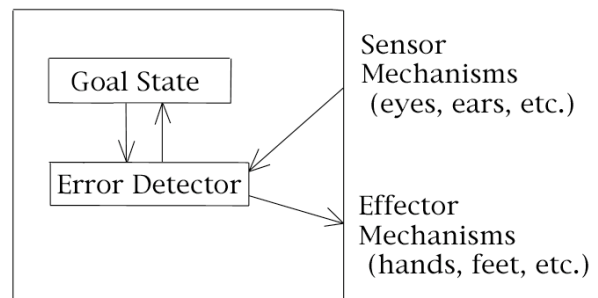


Figure 1: The classic Goal-Directed System of cybernetics. A robot of this design contains a Goal State, that is a hard-wired definition of the desired state of the external world. The Error Detector uses sensory information to determine the difference between the desired and actual states, and takes action through effector mechanisms to realize the desired state.

Much of the interesting technology of robotics concerns the structure of the sensor and effector mechanisms, but the interesting design questions concern the control mechanisms. Here, the classic design includes a control dichotomy: a Goal State – that is, an explicit definition

of the desired state of the external world that the robot will attempt to realize – and an Error Detector – that is, a mechanism for calculating the magnitude of the discrepancy between the actual state of the external world and the goal state, and determining the motor behavior that is appropriate for the robot to undertake. The control dichotomy is an embodiment of the idea that a permanent template defining what the system is to achieve in the wider world is required, in addition to a mechanism that controls robotic behavior.

4. APPLICATION TO SOCIAL ORGANIZATIONS

4.1 Business Systems

Current management theory places extreme emphasis on the efficiency, authority and flow of information in relation to the president or CEO [8], but traditional management theory was concerned more generally with the balance between idealistic long-term planning and more realistic short-term control [9]. It is this division of labor that is at the heart of the structural dichotomy between the executive hierarchy (with the CEO at the top) and the Board of Directors. As illustrated in Figure 2, the Board of Directors is, by design, comprised of senior figures who are less motivated by financial gain than by a sense of idealism concerning what the business can contribute to society. In contrast, the Executive Hierarchy is comprised of younger, more ambitious managers fully absorbed in the day-to-day matters of running the business and selling goods and services. Their guiding philosophy is realism rather than idealism.

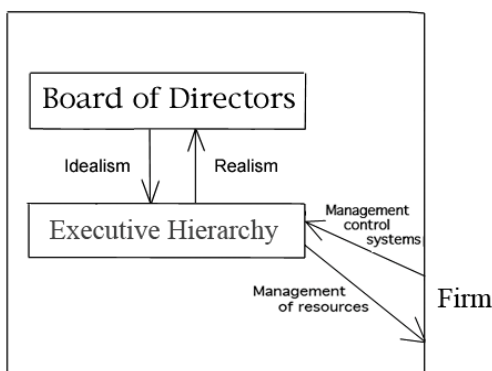


Figure 2: An idealized version of the management structure of a business organization.

There are additional issues in management theory that the cybernetic control dichotomy does not directly address (notably the voicing of labor needs to the

executive hierarchy), but the essential systems theoretical argument is that the viability of any business system depends on an appropriate balance between two diametrically-opposing tendencies. They are the long-term goals of the business – essentially doing business in such a way that the corporate effects will be beneficial to society at large – and the realistic needs of the business to earn a profit to reward its workforce and maintain its commercial viability. In a word, management theory is the art of compromise between these two long- and short-term tendencies, and it is a matter of debate whether the same individuals can usefully contribute to both a Board of Directors and a Management Hierarchy. By implementing a control structure that *explicitly* acknowledges the differences between idealism and realism, between the company’s socially-responsible vision, on the one hand, and its competitive, strategy implementation, on the other, and that maintains an inherent balance between what are potentially contradictory tendencies, the longevity of the business can be promoted – to the benefit of those who work in the stable business system and to the benefit of society at large.

4.2 Nation-States

Debates concerning the best structure of government date from Aristotle, but 20th Century science adds a new perspective. The argument from general systems theory is that “dual control” by two equally-strong branches of government embodies principles of long-term stability and short-term responsiveness, both of which are of likely to be advantageous to citizens living in such nation-states. Much of the “dual control” argument is little more than a restatement of common sense in political science, but the significance of the argument lies in the fact that it is motivated from an understanding of natural, not political, systems. The most fundamental point is that a “bicameral” governmental organization should contain a legislative branch that is removed from direct influence by or over the populace (thus making laws that are of general applicability, and not tailored to transient needs and opportunities). Simultaneously, an executive branch should be in direct contact with the populace – and be responsive to the current situation of the populace. The ongoing “struggle” of politics should therefore take place between these two branches – with the legislature arguing the “conservative” case for the long-term coherency and stability of the state (“conservative” in relation to the ideological content of the laws of the given state) and the executive branch advocating a less-principled, but more empathetic and “liberal” or “progressive” policies designed for the immediate relief of social problems (again, “liberal” in relation to the

established ideology of the nation). The actual contents of laws – i.e., the driving ideology that determines the balance of personal freedom vs. social obligation, the level of taxation, the degree of military strength, the amount of corporate freedom, etc. – are the perennial issues of politics and will be determined by the will of the people in diverse cultures in diverse eras. Therefore, the ideological content of societies cannot, in principle, be decided by abstract considerations for all times and places, but a universal need for balancing long-term idealism with short-term pragmatism is the essence of systemic existence. In analogy with the most successful systems in the natural world, the tension between principle and pragmatism, between stability and flexibility, between idealism and realism, can be instantiated at the highest level of government through dual control structures.

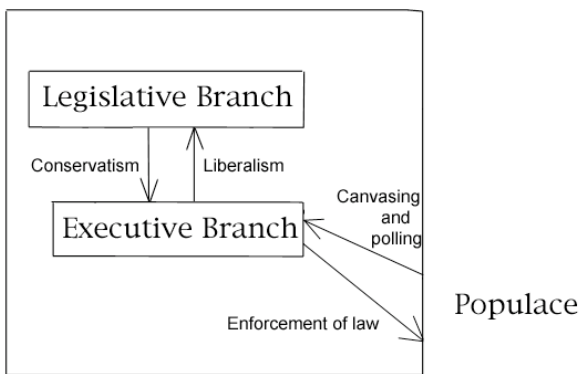


Figure 3: The idealized structure of government, based on the known functional dichotomy in natural systems.

The role of the “third branch of government”, the judiciary, does not lie in the creation, amendment or re-interpretation of law, but in deciding on its proper application – both between the two law-making branches of government and between the executive branch and the populace. (The mechanisms of the democratic election of government officials is a completely separate issue that does not impinge on issues of the structure of government.)

5. CONCLUSIONS

If it is assumed that the stability of organizations is inherently good for the people within the organizations, then it is reasonable to search for design principles that will lead to organizational longevity [10]. The significance of the known functional/structural dualities in natural systems and the existence (and, arguably, dominance) of similar dualities in artificial and social systems is that we have a solid empirical basis for

studying the fundamental structure of viable systems of whatever size or make-up.

Most importantly, the design of artificial and social systems does not need to start from scratch, but can, in principle, benefit from the accumulated knowledge of the natural sciences and at least some empirical input concerning the control structures of currently existing social systems. Needless to say, there are new issues at play in man-made systems and it is not enough simply to draw an analogy from natural systems to provide guidance on the construction of social systems. Nevertheless, natural science provides us with unambiguous examples of successful systems. Moreover, the mechanisms of control are there to be observed – and are less likely to be misinterpreted through ideology than are social systems that human beings cannot, in principle, view “objectively” from the outside.

At the very least, we should design social systems that are consistent with what we know about lower level systems. At its worst, the analogy from natural systems will give us theoretical arguments that, for some reason, we may wish to dismiss as irrelevant. At its best, however, the systemic strengths that are known to be embodied in natural systems might be reproduced in similarly designed social systems. In any event, what a general systems theoretical approach to social systems provides are ideas about social systems that are not elicited from scholars who, however knowledgeable or well-meaning, are already imbedded in, and necessarily reacting to, the social systems in their own lives. In other words, general systems theory [11] offers the possibility of an objective, abstract perspective on the issues of social structures.

Table 2: A Summary of the Central Dogmas of Natural, Artificial and Social Science

<i>System</i>	<i>Control Center (internal)</i>	<i>Dichotomy (external)</i>	<i>Periphery</i>
The Atom	neutrons	protons	electrons
The Cell	DNA	RNA	proteins
The Human Organism	right hemisphere	left hemisphere	body
Cybernetic Systems	goal state	error detector	effector mechanism
Business Systems	board of directors	executive hierarchy	labor force
Nation-States	legislative branch	executive branch	populace

The highest-level division of labor for the control of the known natural, artificial and social systems on Earth can be summarized as in Table 2. It bears emphasizing that the actual mechanisms of information transfer within these various systems are the topics of most research efforts in these fields. Nevertheless, before we get to issues concerning detailed mechanisms, the overall control structures, i.e., the “central dogmas”, provide the context within which such mechanisms work. The central dogmas that have been established in the natural sciences reveal a surprisingly consistent pattern of dual control [2]. Their emergence in the evolution of various material systems can be understood as due to the guiding hand of natural selection. For social systems, the conscious design of viable structures implies a more Lamarckian form of evolution, but again selection pressures determine what structures will and will not survive. Arguably, analogous control mechanisms have already evolved to some extent in a variety of artificial and social systems, but a more systematic application of such ideas might yet prove useful [12].

Philosophical and even political considerations have intermittently had real influences on scientific research, but the experimental nature of research in the natural sciences – with the possibility of replicable, verifiable results that resist all “alternative” interpretations – is the envy of all researchers struggling in the social sciences. Even when there is unambiguous empirical data available to support an argument concerning advantageous organizational structures in social systems, there is never an evolutionary “proof” as strong as those found in the natural sciences. The viability of atomic systems is beyond question, and the central dogma involving protons, neutrons and electrons is known to be the unique organizational principle underlying the building block of all stable physical systems. Similarly, there are no living cellular systems that contradict the central dogma of biology. The global dominance of *Homo sapiens* among animal species (psychological systems) is currently unambiguous, but the evolutionary argument is weaker, insofar as our presence on earth is little more than 2 million years old. In an evolutionary sense, we are still unproven upstarts.

Be that as it may, the current dominance of social systems – business organizations or political states – is, from an evolutionary perspective, far too brief to indicate true longevity. Moreover, there is no possibility for objective verification of which social structures will prove viable in the long-term. For this reason alone, the application of design principles that have a foundation in the natural sciences is desirable.

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