Chapter 5
Organisms Need Mechanisms; Mechanisms Need Organisms

William Bechtel and Leonardo Bich

Abstract According to new mechanists, mechanisms explain how specific biological phenomena are produced. New mechanists have had little to say about how mechanisms relate to the organism in which they reside. A key feature of organisms, emphasized by the autonomy tradition, is that organisms maintain themselves. To do this, they rely on mechanisms. But mechanisms must be controlled so that they produce the phenomena for which they are responsible when and in the manner needed by the organism. To account for how they are controlled, we characterize mechanisms as sets of constraints on the flow of free energy. Some constraints are flexible and can be acted on by other mechanisms, control mechanisms, that utilize information procured from the organism and its environment to alter the flexible constraints in other mechanisms so that they produce phenomena appropriate to the circumstances. We further show that control mechanisms in living organisms are organized heterarchically—control is carried out primarily by local controllers that integrate information they acquire as well as that which they procure from other control mechanisms. The result is not a hierarchy of control but an integrated network of control mechanisms that has been crafted over the course of evolution.

Keywords Autonomy · Control mechanisms · Constraints · Free energy, heterarchical organization · Mechanistic explanation

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5.1 Introduction

Among the entities in the universe, organisms are highly unusual. They are complexly organized systems made of soft materials that tend to degrade, yet they maintain themselves far from equilibrium. This requires regular work—an organism must extract free energy and materials from the environment and utilize them to construct, repair, and maintain itself. When organisms stop performing this work, they die and decay (generally assisted by other organisms that use the matter and energy accessed from the dead organism for their own self maintenance). Although all individual organisms eventually die, all organisms now alive are parts of continuous lineages of organisms which, over a span of more than three billion years since the origin of life, maintained themselves and produced successors.

To perform the work needed to maintain themselves, organisms rely on mechanisms—sets of components organized to carry out different activities in a coordinated fashion. As envisaged by some new mechanists, mechanisms are active—according to Machamer et al. (2000), a mechanism produces a specific phenomenon whenever its start-up conditions are realized.[1] What phenomenon? The phenomenon the mechanism is equipped by its constitution to produce. These phenomena (e.g., protein synthesis, generating action potentials, cell division) are far less complex than life itself. In advancing their account, mechanists have had little to say about whole organisms and how they act to maintain themselves. They seem to treat organisms as simply collections of mechanisms. If mechanisms are construed, as they are by the new mechanists, as each responsible for one phenomenon, then the organism must consist of just the right set of mechanisms to generate each phenomenon when it is needed so that the organism is maintained. Given the constantly changing conditions that organisms confront, it is extremely unlikely that even a powerful process such as evolution by natural selection could have equipped organisms with just the right set of single-phenomenon mechanisms to jointly execute the actions organisms need to survive. This seems even less likely when one recognizes that organisms are also agents which change their environments and thereby alter what activities they must perform to maintain themselves. A minimal step to overcoming this challenge is to reconceptualize mechanisms so that they are capable of producing different phenomena as required by the circumstances an organism finds itself in. In Sect. 5.2, we offer a revisionist account that characterizes mechanisms in terms of constraints on flows of free energy and show how it provides for a more dynamical account in which mechanisms can be controlled so as to perform different activities as needed.

A different tradition of theorists, constituting the organization or autonomy school, has focused directly on the ability of organisms to maintain themselves. Theorists in this tradition address such topics as the ability of organisms to construct themselves (Maturana & Varela, 1980), repair themselves (Rosen, 1991), and

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[1] Bechtel and Abrahamsen (2009); (see also Abrahamsen & Bechtel, 2011) also view mechanisms as capable of endogenous activity, but for them that is a consequence of cyclic organization.

manage thermodynamic processes (Moreno & Mossio, 2015). This tradition treats organisms as the active entities—they act to maintain themselves. It is, however, challenging to explain how organisms themselves have such capacities: what is the organism to which such actions are attributed? The organism is the whole organized system comprising its various components. It is not something additional to its constituents that has its own powers (Ryle, 1949). To explain how the organism carries out any given activity needed to maintain itself, scientists appeal to its component mechanisms and what they do. Each activity an organism performs results from the operation of specific mechanisms in it. In what sense is the organism, not the component mechanisms, responsible for carrying out the appropriate activities?[2] Here the autonomy school[3] offers an important insight—each mechanism that carries out an activity needed for the organism to maintain itself is the product of closed loops of processes within the organism. Different theorists characterize how these processes are closed in different terms. For Maturana and Varela, it is closure of construction (autopoiesis), for Rosen, closure of efficient causation, and for Moreno and Mossio, closure of constraints. We discuss the different conceptions of closure in Sect. 5.3, showing that the notion of closure of constraints offers the greatest promise for understanding organisms as maintaining themselves.

Having characterized both mechanisms and autonomy in terms of constraints, we explore how a focus on constraints can serve to integrate these perspectives in Sect. 5.4. The key to doing this is developing an account of how mechanisms can act on the constraints of other mechanisms. We treat mechanisms that act on the constraints of other mechanisms as belonging to a distinct type of mechanism, *control mechanisms*. Most of the mechanisms characterized by the new mechanists are what we term *production mechanisms*—mechanisms that constrain free energy to carry out a productive activity—constructing something, moving it about, or taking it apart. On our conception of mechanisms, mechanisms perform specific productive activities due to how constraints realized in them direct flows of free energy. Control mechanisms, as we understand them, also operate as a result of constraining flows of free energy, but do so to modify constraints in other mechanisms, thereby determining how those mechanisms operate.[4] Thus, control mechanisms direct the activities of production mechanisms. If closure of constraints is to explain how organisms are capable of acting to maintain themselves, then we must characterize how the constraints in control mechanism are part of the closed system. This is tricky since, for control mechanisms to do their job, the constraints realized in them at a given time need to be responsive to conditions external to themselves. We will

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[2] Each composite of mechanisms can, of course, produce different activities. This is due to how the components are organized.

[3] Another term applied to the autonomy school is the organization school. The key thing to emphasize is that the activities of an organized system are due to the components acting together within the overall organization.

[4] A notable feature of control mechanisms is that generally they require much less energy than production mechanisms. It takes much less free energy to move a switch than it does to operate a motor.

develop an account of how control mechanisms can be open to information they procure from the environment and yet part of a closed network in the sense required for their activities to be viewed as activities of the organism.

In thinking about control, especially in the design of social and political institutions, we often think hierarchically — local controllers report to a smaller set of controllers at the next level and at the top is the chief executive that controls the whole institution. This perspective is sometimes adopted in thinking about biological organisms—theorists might conceptualize the nervous system as controlling an organism's body and as itself organized hierarchically such that higher centers in the brain control others. This, however, misrepresents how control mechanisms in biological organisms are organized—much control remains local and multiple local controllers coordinate their activities to accommodate the diverse needs of the organism without any one controller being in charge. We develop this understanding of heterarchical control in Sect. 5.5 before concluding in Sect. 5.6.

5.2 Constraints: A Revisionist Account of Mechanisms

The new mechanists articulated their concept of mechanism as they sought to understand the practices of biologists who frequently appeal to mechanisms in their explanations of biological phenomena (Bechtel & Richardson, 1993/2010). Taking their lead from the fact that biologists develop their mechanistic accounts by decomposing systems taken to be responsible for a phenomenon into their constituents, the new mechanists characterized mechanisms in terms of constituent entities or parts,[5] the activities or operations performed by these entities, and how they are organized to produce the phenomenon (Machamer et al., 2000; Bechtel & Abrahamsen, 2005; Glennan, 2017). In developing their account, Machamer et al. chose the term *activity* to emphasize that mechanisms do things and insisted on a dualism of entities and activities. On their construal, the activity of a whole mechanism results from the activities of their component entities. This seems to introduce a regress in which to explain any activity one must decompose a given mechanism into its component activities. Machamer et al. seek to stop the regress by noting that in practice the explanations researchers advance bottom-out with components whose activities are simply accepted and not further explained. Whether one terminates the decomposition at a given point or continues further down, the notion of activity remains a primitive that is not itself explained (in particular, on their view, it is not explained by the entities that constitute the mechanism).

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[5] Philosophers of science who have advanced a process metaphysics (see various contributions to Nicholson & Dupré, 2018) have criticized the mechanists appeal to entities or parts, construing the mechanists as treating these as unchanging *things*. It is important to recognize that new mechanists do not view mechanisms or their components entities or parts as unchanging. The entities constituting mechanisms change as mechanisms operate and as they are constructed, repaired, and eventually deconstructed.

A different approach is to appeal to how physicists explain changes in the world. They commonly appeal to Gibbs free energy. Although matter and energy are viewed as interconvertible, the differentiation of matter and energy itself represents a dualism. It is a dualism, however, that is grounded in basic laws thought to govern the universe. According to thermodynamics, maximal free energy was available at the origin of the universe when matter was unequally distributed and dissipates as matter becomes more homogeneously distributed. The second law of thermodynamics asserts that in any closed system, free energy continually dissipates as the distribution of matter goes to equilibrium. Available energy due to disequilibrium within a system can be used to produce mechanical work. It can only do so, however, when it is constrained—left unconstrained, free energy is lost as the system goes to thermal equilibrium.

Thus, the key to the ability of a system such as a mechanism to perform work is that free energy does not simply dissipate but does so in a constrained manner (Kauffman, 2000). The notion of constraint was introduced into classical mechanics to account for macroscale objects. On its own, each elementary particle can move in any of six dimensions (three spatial, three rotational). But when these particles are bound to each other (e.g., through chemical bonds), they are constrained to move with the composite object. When a force is applied to the composite object, its components move with it due to the constraints. The notion of constraint can be extended to thermodynamics: how free energy dissipates is constrained by the current structure of the system. For example, when free energy is released by combustion in the cylinder of a gasoline engine, it is constrained to move against the piston, thereby performing work (Hooker, 2013).

A focus on constraints as physical structures that limit the flow of free energy is crucial in understanding how biological organisms direct free energy into the production of work. We cannot provide a thorough discussion of constraints here, but note two important features of constraints. First, in conceptualizing a structure as a constraint, one needs to specify the time-scale during which it serves as a constraint. As physical structures, constraints can and are changed by flows of free energy. Distinguishing a constraint from the process of energy flowing through the constraints to produce work, Mossio et al. (2013) contend that at the time-scale characteristic of the process, the constraint is locally unaffected by the process—the constraint is not part of the process and is stable during it. Moreover, at that time-scale, the constraint exerts a distinctive causal power on the process, limiting the range of possible outcomes (degrees of freedom) of the process. Second, although the term *constraint* emphasizes that constraints impose limits, Kauffman (2000) and Hooker (2013) among others, have developed how constraints are also enabling as they create new possibilities. By canalizing the flow of free energy, constraints enable outcomes that otherwise would be extremely improbable or practically impossible. When water flows downhill, free energy is dissipated. But if it is limited to flowing through a pipe, the water in a reservoir can reach a distant tank that it would not otherwise reach. As a result of the pipe, water molecules that might have flowed in different direction are limited to following in the same direction. If further constraints are added, this directed flow of water can be used to carry out other activities, such as moving the wheel of a water wheel, resulting in the milling of grain that would not otherwise be turned into flour. Hooker also provides an illustrative biological example: a skeleton restricts the movements an organism can make, but also enables it to move in ways it couldn't otherwise.

Winning and Bechtel (2018) adapted this perspective on free energy, constraints, and work to characterizing mechanisms. They viewed the components of mechanisms as imposing constraints restricting the flow of free energy. On this view, biological mechanisms are active not because they are composed of activities, but because they constrain free energy so as to perform work—to generate the phenomenon for which the mechanism is taken to be responsible. On the conception of mechanism proposed by Winning and Bechtel, mechanisms should not be understood simply as organized sets of entities and activities, but as organized sets of constraints (entities, parts) that direct the flow of available free energy so as to carry out work (generate the phenomenon). The notion of activity (or operation) still has a place in this account—as researchers decompose the mechanism in their attempt to understand how it generates the phenomenon, they will focus on the activities of individual components of the mechanism. These activities, however, will not be treated as primitives, but as the product of the constraint of free energy by particular components of the mechanism.

Although philosophical accounts of mechanism prior to Winning and Bechtel did not attend to the role of free energy in mechanisms, it has clearly been central to biological thinking since the pioneering work of Lavoisier and LaPlace (1780), who characterized the metabolic activities of animals in terms of combustion. One of the most prominent physiological chemists of the nineteenth century, Liebig (1840), sharply distinguished between plants as synthesizing energy rich molecules such as sugars, and animals as acquiring energy by catabolizing them. Although this simple assignment of synthesis to plants and catabolism to animals was soon recognized as too simplistic as animals also carry out synthesis, physiologists focused on heat as the energy currency of animals (Mendelsohn, 1964). This changed with the discovery that adenosine triphosphate (ATP) provided the free energy for animal activities such as muscle contraction (Fiske & Subbarow, 1929; Lohmann, 1929). Due to the unusual amount of free energy liberated by the hydrolysis of ATP to adenosine diphosphate (ADP), the bond to the third phosphate group came to be regarded as a "high-energy" bond and the primary energy currency in animals. Initially, physiologists could do little more than correlate ATP synthesis with the catabolism of sugars, fatty acids, and other molecules and the hydrolysis of ATP with activities such as muscle contraction. For example, after (Huxley, 1969) advanced the swinging-crossbridge model of how myosin exerted force on actin in the course of muscle contraction, Lymn and Taylor (1971) associated each step with a step in the process of ATP hydrolysis. By the 1990s, though, researchers began to explicate this process in terms of the chemical bonds formed between a substrate and ATP that enabled the energy liberated in hydrolysis to be constrained within myosin so as to move another part of the molecule, referred to as the lever arm, whose movement exerted force on actin (Fisher et al., 1995; Holmes & Geeves, 2000; for theoretical analysis, see Bechtel & Bollhagen, 2021). Similar analysis of the molecules involved in ATP synthesis showed how free energy captured in a proton gradient in the mitochondria generated force within the F_OF_1ATPase that brings ADP and Pi into juxtaposition so that they form a bond.

The ability to analyze the flow of free energy in terms of forces exerted in molecular structures is still only possible in limited cases.[6] In many cases, physiologists can only appeal generally to the role of ATP in supplying the source of free energy. This is especially true at higher levels of organization in which researchers characterize the activity of muscle in phenomena such as the pumping of the heart or how foodstuffs are broken down and transferred through the organs of the digestive tract. Although they cannot show in detail how the energy released by hydrolysis of ATP is constrained so as to create force that results in the physical work, they nonetheless frequently identify where hydrolysis occurs that provides the needed free energy for a given mechanism to operate. What the revisionist account of mechanism makes clear is that what the biologists are envisaging is constraints restricting the flow of free energy through mechanisms.

An important benefit provided by the revisionist account in contrast to standard new mechanist accounts (e.g., Machamer et al., 2000; Bechtel & Abrahamsen, 2009; Glennan, 2017) is that it makes clear how mechanisms are dynamic, capable of varying their operation and even carrying out multiple activities. Most new mechanists have embraced what has been referred to as Glennan's law which identifies one mechanism with one phenomenon.[7] Bollhagen and Bechtel (2022) have shown that in practice, once researchers have used the characterization of a phenomenon to pick out a mechanism, they anchor their further investigations on the mechanism itself. This sometimes leads to discovering that the same mechanism is responsible for different phenomena. For example, it is not uncommon that, after discovering the mechanism responsible for a phenomenon, researchers determine that it often autoinhibits—prevents itself from operating except when conditions require its operation. This is made possible by the fact that not all the constraints constituting a mechanism are fixed. Some can be acted on and changed.

Even the production of the initially characterized phenomenon typically requires that constraints within the mechanism be changed as energy is directed through the mechanism. For example, in a human-made machine such as a car engine, the piston moves as a result of the free energy released through the combustion of gasoline. Pistons are connected through the camshaft so that, as one piston moves, it applies force to others. Among other things, this compresses the gasoline in another cylinder. Once compressed, a spark initiates its combustion, which acts on the first piston, returning it to its original position to begin another cycle of activity. A similar

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[6] This is changing rapidly. See, for example, Swan et al. (2021) for an account of how ATP hydrolysis generates movements within KaiC that provides the free energy for the cycle of events that constitute a circadian cycle in cyanobacteria.

[7] Glennan (1996) argued that "One cannot even identify a mechanism without saying what it is that the mechanism does." An exception to the widespread endorsement of this contention is Bechtel and Abrahamsen's (2005, p. 423) acknowledgment that a mechanism may be "responsible for one or more phenomena."

cycle of changing flexible constraints figures in the action of myosin—the hydrolysis of ATP results in changing the constraints within myosin, altering its ability to bind actin and to exert force on it, culminating in it expelling ADP and binding a new molecule of ATP. In these processes, constraints result in movement that changes the constraints, altering subsequent movement.

In addition to being changed in the normal working of a mechanism, constraints can be changed by other mechanisms working on it. By changing the constraints in a mechanism, these other mechanisms can change how free energy flows through the first mechanism and thus what work it performs. To illustrate this, we return to the case of actin and myosin. By default, the sites at which myosin can bind actin are blocked by tropomyosin binding to them. When calcium ions (Ca^{2+}) are released into the cytoplasm, they bind tropomyosin and remove it from the myosin binding site. Normally whatever Ca^{2+} is in the cytoplasm is taken up in the sarcoplasm reticulum, but when signaling proteins bind receptors on the sarcoplasmic reticulum, they change constraints in those receptors, allowing Ca^{2+} to flow into the cytoplasm and remove tropomyosin, allowing myosin to bind and exert force on actin.

In Sect. 5.4 we will characterize mechanisms that change constraints within other mechanisms as control mechanisms. But first we turn to the autonomy tradition, which has also foregrounded the notion of constraint and made it central to the account of closure that renders organisms autonomous.

5.3 Autonomy and the Closure of Constraints

Kant (1790/1987) famously advanced the idea that organisms are self-determining—are autonomous. This meant that some of the causes of the existence of an organism are not external and independent from it, but depend on the very organism that they help to generate. Another way to state the Kantian idea is that the system and its components are mutually dependent, as the components exist for the whole they generate and the whole exists for the components it produces and maintains. The challenge is to work out just what this entails. Piaget (1967), Rosen (1972), and Maturana and Varela (1980), among others, emphasized that organisms are systems organized in such a way that they are capable of constructing, repairing, and maintaining their parts, and consequently themselves, through the continuous exchange of matter and energy with the environment—they are autopoietic. Insofar as the functional components responsible for these activities are made by the organisms themselves (or by their predecessors), what the components do can be viewed derivatively as activities of the organism. Maturana (1980, p. 48) comments "The living organization is a circular organization which secures the production and maintenance of the components that specify it in such a manner that the product of their functioning is the very same organization that produces them."

The idea of autonomy was built on two main notions, as introduced by Piaget and further elaborated by the others. The first is *thermodynamic openness* (or openness to material causation, in Rosen's vocabulary): an organism needs matter from the environment in the form of building blocks from which to produce its components, and energy to perform the activities required to achieve self-production, self-repair, and self-maintenance and to interact with a changing environment. The second notion, which is distinctively biological, is *organizational closure* (or *closure to efficient causation*, in the case of Rosen): a biological organization is characterized as a closed network of processes of production in which each component is produced by others in the network such that the network maintains itself.

Departing from the traditional characterization of organizational closure and inspired by the work of Pattee (1972, 1973/2012) and Kauffman (2000), Moreno and Mossio (2015) emphasize the thermodynamics of organisms in a way that goes beyond the idea that organisms just need matter and energy—organisms must constrain free energy in constructing and maintaining their own components. The components that contribute to the construction and maintenance of a biological organism are characterized as constraints. These constraints canalize free energy into performing biological processes, including those responsible for the generation of other constraints. On this view, organisms must perform work to produce and maintain the very constraints that make the performance of work possible. The resulting account is one of *closure of constraints*: the existence and activity of the constraints operative in a living system depends on the action of other constraints in the system that direct the flow of free energy into their establishment.

Constraints can be organized in cycles: a constraint that enables one activity can be set by another simultaneous constraint, with each determining the other. However, the notion of closure involves a regress in which each constraint is constructed by the activity of one or more preexisting and already operative constraints until one arrives at the initial constitution of the organism. As a matter of fact, at birth some of these constraints are inherited from those produced by the parents (see Mossio & Pontarotti, 2022), but most of the constraints constituting an organism at any given moment have been produced, replaced, repaired and maintained by the organism during its lifetime.

The notion of closure of constraints fits well with the revisionist conception of mechanism explained in Sect. 5.2 as the appeal to constraints in Moreno and Mossio's account echoes the appeal to them in the revisionist account of mechanism. On both accounts, each activity of an organism is carried out through the constrained release of free energy. This is not surprising, as both accounts drew inspiration from Pattee. In this specific respect, one point of divergence between the two account concerns the entities responsible for those biological activities that, in the autonomy perspective, would coincide with biological functions as they contribute to the maintenance of the organism (Mossio et al., 2009). According to the account of closure of constraints, each of these functional activities is performed by one constraint, and closure consists in the mutual dependence between these functional constraints. To characterize these biological activities, the revisionist account of mechanism looks, instead, at organized sets of constraints, that is mechanisms, where the mechanisms are characterized by how they constrain the release of free energy.

As argued elsewhere (Bich & Bechtel, 2021), associating a single constraint with a biological function is an abstraction. While useful in some cases for explanatory purposes such as when considering an enzyme catalyzing a reaction, it risks overlooking the complexity underlying the realization of a biological function and how this complexity matters for the overall functioning of the system. Already in the relatively simple case of an enzyme, different parts, such as the catalytic site, the phosphorylation and allosteric sites, structures that undergo conformational changes, etc., contribute differently to the function performed by the enzyme. This function would be better characterized in terms of a mechanism employing several interacting constraints. This is even more evident in the cases of systems composed of components whose activity depends in turn on the interaction between different sub-components, such as in molecular complexes in cells. Likewise, in multicellular organisms, the activity of organs depends on the interaction of different structures (such as the muscles, valves, etc. in the heart) or cell types (for example alpha and beta cells, among others, in the pancreas) constituting them.

A possible way to connect closure of constraints and the revisionist account of mechanism is to consider functions as performed by mechanisms, which in turn are defined by their constraints. An interesting consequence of this conceptual step, which has plenty of implications to be explored in further work, is that biological mechanisms, and the constraints that they harbor, can be considered in the context of closure as dependent on the activities of other mechanisms (organized sets of constraints) in the organism.

At this point it is important to point out that this conceptual step is not as simple as it might seem at first sight and taking it would not be uncontroversial. New mechanism and autonomy are two complex frameworks which, however related and often intersecting or complementary, do not perfectly overlap, as they have different foci, strategies and different questions to which they aim to respond (Bich & Bechtel, 2022b). Closure of constraints differs from mechanistic accounts in that it emphasizes the relations between activities that contribute to the maintenance on the system, rather than between the component activities that mechanists treat as giving rise to phenomena. Moreover, it treats the organism as a whole as the starting point and the main focus when addressing what is distinctive about living organisms. It aims to identify what functions are necessary to produce and maintain it and how they depend on one another, rather than to explain how a specific biological phenomenon is materially realized. In doing so, work on autonomy does not engage in decomposition in the same way as described by the mechanists. Yet if one accepts that biological functions require mechanisms made of constraints rather than individual constraints, and considers the role of constraints in defining mechanisms, one might go as far in bringing the two frameworks together as to consider that organizational closure may be recharacterized as a special type of closure of mechanisms.

However, as we develop in the next sections, closure alone, although a fundamental notion, cannot account for the distinctive causal regime at work in biological systems. Control also plays a central role and needs to be taken into account.

5.4 Control Mechanisms

In discussing mechanisms in Sect. 5.2, we noted that the constraints that determine how a mechanism will behave can be influenced by other processes outside the mechanism. Such a process can itself be construed as due to the work of a different type of mechanism that constrains free energy to act on the constraints in the production mechanism. We refer to such mechanisms as *control mechanisms*. In order for control mechanisms to produce changes in production mechanisms that are appropriate to the circumstances within or confronting the organism, control mechanisms must be able to procure information about these circumstances. Following Pattee, we will characterize the process by which they do so as *measurement*. What this requires is that the constraints in control mechanisms that determine what action they perform be responsive to the circumstances within and confronting the organism. Many organisms rely on detecting chemicals in their environment and moving as a result. The chemicals alter constraints in the sensors and the altered constraints in the sensors result in changes in the production mechanism, altering what it does.

Allowing measurements to affect the constraints in control mechanisms seems to be in tension with the account of closure of constraints developed in Sect. 5.3. That required that each constraint, and hence each mechanism, be itself the product of work performed by other constraints constituting other mechanisms within the organism. But in order to make measurements, these constraints must be modified by what is being measured. Especially when control mechanisms make measurements of conditions external to the organism, this seems to undermine closure—a given constraint is causally modified by things other than the constraints constituting the organism.

The resolution to this challenge is to recognize that measurement is a different type of interaction from those involved in the production and maintenance of a constraint within a regime of closure. To see how closure of constraints can be maintained even as control mechanisms make measurements, we need to distinguish a constraint itself from the particular forms it may take. Consider a mechanical thermostat that controls a furnace by registering the temperature through a bimetallic coil. Higher temperatures cause the outer strips to expand more than the inner strip, resulting in the strip curving away from the point of contact that completes the circuit to the furnace, breaking the circuit. We can distinguish the constraints constituting the thermostat from the curvature of the strip at a given time. Both are involved in the action on the furnace, but the fixing of the constraints that constitute the thermostat—the constitution of the strip from two metals and the positioning of the contact point—is different from the fixing of the curvature on a particular occasion. The constitution of the thermostat determines what it can measure while the ambient air determines the actual measurement. A thermostat is designed to be informed by the temperature of the air and so is open to information. The same applies to control mechanisms within an organism such as a chemosensory neurons, except now the constitution of the measuring device is the product of the closed system of constraints constituting the organism. The constraints that enable the neuron to measure the presence of a given chemical are established through the activity of other mechanisms within the organism while its actual registration on a given occasion carries information about the chemicals in the environment of the neuron. Control mechanisms are open to information even as the constraints that constitute them and enable them to do so are determined by other constraints with the organism, preserving closure.

Closure requires that each control mechanism operative in an organism be itself the product of another mechanism within the mechanism. Since causes must precede their effects, closure inevitably takes us back to the initial constitution of the organism. What is present at the beginning of the life of an organism is itself the product of another organism from which it was generated. Among other things, an organism begins life with both the mechanisms needed to recruit and constrain energy and its genetic material. While not acting on their own, genes play an important role in determining what further mechanisms the organism will construct, both production mechanisms and control mechanisms. Synthesis of new proteins involves transcription factors initiating the transcription of the sequence of nucleic acids constituting DNA into a corresponding sequence of nucleic acids in RNA, which is then, in the case of eukaryotic organisms, transported to the ribosomes in the cytoplasm, where it is translated into a corresponding sequence of amino acids. These are folded, often with assistance of other proteins, into proteins in the endoplasmic reticulum. Some of the newly minted proteins are prepared for export out of the cell in the Golgi apparatus, but others are incorporated into the structure of the cell, where they catalyze biochemical reactions. Genes thus provide a template for the proteins that subsequently perform the various activities cells carry out to maintain themselves. In providing such a template, genes quite literally inform (specify the constitution) of proteins. Genes have, accordingly, been viewed as constituting information. But there is a significant difference between the informational role of genes and that of external conditions measured by an organism's sensory systems. The information in genes determines (up to a certain degree) the constitution (the sequence of amino acids) of mechanisms, including control mechanisms. Other components of the new organism (acquired in part as a result of interacting with entities in the environment) determine which of these mechanisms will be constructed by determining which genes will be expressed.

At the outset and throughout life, genes specify the structure of the mechanisms constituting the organism. Transcription factors, and the mechanisms producing them, determine which genes will be expressed. Once produced, some of the resulting proteins constitute control mechanisms. Some control mechanisms determine subsequent gene expression and hence the constitution of subsequent mechanisms. These control mechanisms are informed not just by genes but by measurements the control mechanisms make. Measurements, as we discussed above, don't directly determine the constitution of the control mechanism but rather influence the form it takes, typically in a variable manner. However, over time they do end up contributing to the constitution of the organism by determining which genes are expressed (as well as what posttranslational modifications are made to the product proteins). Whereas at the outset all of the machinery constituting the organism originated in the parent organism, over time the machinery reflects both its initial constitution and its experiences.

In this section we have developed the conception of control mechanisms as mechanisms that direct the productive activities of organisms while taking into account information reflecting the organism's condition and environment. They are the vehicle through which organisms determine how they will act to generate, repair, and maintain themselves. In virtue of each production and control mechanism being generated from other mechanisms constituting the organism, organisms manifest a closure of constraint even as they remain open to information and alter their behavior in light of this information.

5.5 Integrating Control Mechanisms

Our characterization of control mechanisms identified two features—a measurement process that affects the constraints constituting the control mechanism and the action of those constraints on the constraints of other mechanisms (production or control mechanisms). The components of a control mechanism responsible for measurement and for acting on constraints in other mechanisms can be tightly coupled, as they are in a thermostat. But they can also be separated, with multiple components intervening between those carrying out the measurement and those acting on other mechanisms. Just as it is sometimes helpful to decompose production mechanisms into component production mechanisms, sometimes it is useful to decompose control mechanisms into component control mechanisms. For each of the component control mechanisms to satisfy our characterization of a control mechanism, each must make measurements and carry out action on other mechanisms. This can be accommodated if we view the connection between the two control mechanisms as involving signals—the generation of entities whose role is to be measured by another mechanism. Then one control mechanism can be viewed as generating the signal while the other can be viewed as measuring it by allowing its constraints to be informed by the signal (Fig. 5.1, top). These components can be separated by a distance but still work together in exercising control over a production mechanism.

Allowing for signals between control mechanisms greatly expands the potential for control. The same initial component that makes a measurement can generate multiple signals that are responded to by different control mechanisms, thereby allowing one measurement to effect control over multiple production mechanisms. Or the same downstream control mechanism can respond to signals arising from multiple control mechanisms and thereby respond to different measurements (Fig. 5.1, middle). These possibilities can be combined in various ways, resulting in multiple control processes interacting with each other (Fig. 5.1, bottom). The result might be viewed as a network of control mechanisms.

A network of control mechanisms is not just a theoretical possibility. It appears to be what exists in living organisms, including mammals. Even the simplest organism consists of multiple production mechanisms and individual production

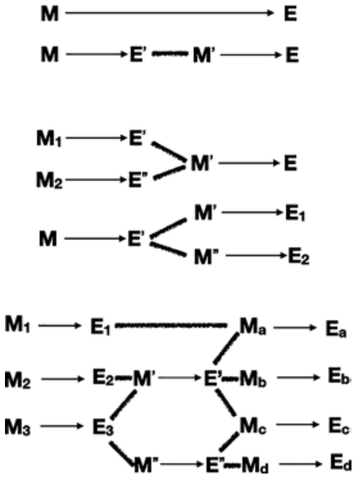

Fig. 5.1 Complex interactions of control mechanisms. Top: a signal can mediate between two components of a control mechanism. Middle: one control mechanism can respond to signals from two different control mechanisms or one control mechanism can release a signal that is responded to by two different control mechanisms. Bottom: different control processes can be integrated into a network

mechanisms can be regulated by multiple control mechanisms, where these are connected by signals (Bich & Bechtel, 2022a). The multiplicity of control mechanisms raises the prospect that different control mechanisms will result in inconsistent actions, presenting challenges for the ability of the organism to maintain itself. How can multiple control mechanisms act to enable the organism to maintain itself?

One way to make individual components work together is to bring them under a single control mechanism that directs all of their activities. The framework we have developed allows for conceptualizing control in hierarchical terms. One control mechanism can operate on the constraints of multiple others (Fig. 5.1, middle). We can characterize the one operating on the others as at a higher level of control (Fig. 5.2a). This consolidation of control can be iterated over multiple levels with fewer controllers at each level in the hierarchy until there is just one at the top level. If the highest-level mechanism is appropriately constituted, it can impose directives on those below it so that, at the bottom of the hierarchy, production mechanisms operate in appropriate ways with respect to each other—e.g., different muscles contracting either simultaneously or in a specified sequence.

Hierarchical control is an intuitively attractive solution to insuring coherent operation of production mechanisms. It comes, however, with a significant cost—if it is to enable the organism to survive, the control mechanism at the top of the hierarchy must acquire all the information required to select appropriate actions. It must be constituted to make all the relevant measurements and, based on them, execute commands for all the appropriate actions. Such a hierarchy is compatible with lower-level control mechanisms procuring information appropriate to executing activities delegated to them. But if the organism is to maintain itself, the highest-level control must receive the information needed to determine the directives to send to control mechanisms subordinate to them in all the situations that the organism might confront. This would require an extremely sophisticated homunculus.

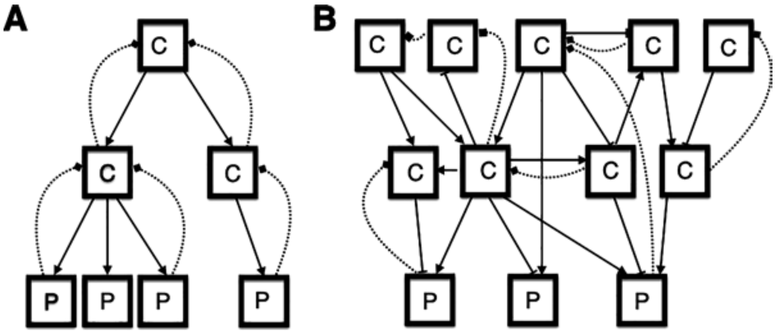

Fig. 5.2 (**a**) Hierarchical organization with information being transmitted to higher-level controllers (dotted lines) and control being executed (solid arrows) on production mechanisms or lower-level controllers. There are fewer controllers at each level, culminating in a single executive controller. (**b**) Heterarchical organization in which multiple controllers can operate in single production mechanisms. Although still presented in terms of levels, the occurrence of arrows directed horizontally and upwards indicates that the ranking of levels is breaking down. There is no single controller at the top. One might better characterize **b** as a network involving interactions that, in the case of control relationships, are only locally hierarchical

Hierarchy is not the only option. Human preferences not infrequently violate hierarchical preferences: an individual prefers A to B, B to C, and C to A, Yet people still function well in the world.[8] For such non-hierarchical relations, McCulloch (1945) coined the term *heterarchy*. We can extend this concept to control mechanisms: it is possible for an organism to be so constituted that mechanism A controls mechanism B, B controls C, and C controls A. As with heterarchical preferences, heterarchical controllers may not be problematic: the different controllers might each respond to different information and may work together in different combinations to enable an organism to cope successfully with different environments. There is, moreover, no reason to restrict this scenario to three control mechanisms organized in a circle. Organisms consist of a multitude of control mechanisms, many of which act on other control mechanisms as well as production mechanisms. On this scenario, an organism consists of a network of control mechanisms that interact with each other in a multitude of ways (Fig. 5.2b). As long as each controller is a product of production mechanisms within the organism, one can have a highly dynamic network of controllers without violating closure.

Control mechanisms can be organized in a heterarchical manner that results in an organism responding to conditions it faces in ways that maintain itself. But the variety of heterarchical arrangements is immense and most heterarchical organizations of control processes are unlikely to result in an organism maintaining itself. Which types of heterarchical organization are likely to be successful? Rather than approaching this question a priori, we suggest drawing inspiration from biology. Control

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[8] This can result in incoherent behavior, but it needn't. If one only confronts pairwise choices, then in each instance the relevant preference can yield a decision.

systems in current biological organisms have demonstrated success since they have succeed in keeping organisms earlier in the lineage alive. Because they are more familiar to most readers, we will focus on mammals.

Many of the control processes in mammals involve neurons, of which many are situated in the brain. Often neuroscientists focus their inquiries on the most recently evolved part of the brain—the neocortex. Within the neocortex, they often conceptualize the frontal regions of the neocortex as the central executive directing the activities of the organism. In doing so, researchers are implicitly assuming that neural control is organized hierarchically. But Sterling and Laughlin (2015) offer a contrary perspective, arguing that a principle exemplified by brains is local control. Another principle exemplified in brains, they argue, is to use chemistry whenever possible. This may seem surprising in an account that focuses on the brain since brains are often characterized as electrical processing systems. Neurons, however, carry out their control processes chemically. Neurons receive inputs from other neurons when neurotransmitters bind to their receptors and respond by performing chemical reactions (Bechtel, 2022). These may involve opening and closing ion channels, thereby affecting electrical currents across that cell's membranes. But in many cases, they carry out a variety of chemical reactions that alter the metabolism of the neuron. These activities include synthesizing new proteins. Moreover, many control activities of neural systems involve acting on the endocrine system, through which cells release molecules that travel through extracellular space (e.g., the blood stream) and act on other cells through receptors at their surface. The endocrine system is an important control system that often exercises control locally within tissues. Whether in the endocrine system or in the central nervous system, much control is carried out locally and chemically.

The role of control mechanisms is to enhance the probability that internal and external activities of the organism are performed when and in the way that is needed for and compatible with the maintenance of the organism itself (Bich et al., 2016). However, another primary role of control in keeping organisms alive is to maintain production mechanisms in conditions in which they can operate. The importance of this was emphasized by one of the first biologists to emphasize the control of biological mechanisms—Claude Bernard. Bernard (1878) described each production mechanism as operating to maintain the fixity or constancy of what he termed the *internal environment*. For Bernard, the result was to free birds and mammals from the vicissitudes of the external environment: whenever factors in the external environment perturbed conditions within the organism, one or more mechanism would be activated to perform its activity to restore the internal environment. As a result, each mechanism could rely on a stable internal environment and was free from the vicissitudes of the external environment.

Bernard did not describe the processes whereby such control was executed. This endeavor was taken up by Cannon (1929, 1932), who introduced the notion of *homeostasis* to characterize the processes through which organisms maintain themselves in similar conditions. In particular, he pays specific attention to the maintenance of some of the features of the "fluid matrix of the body" (citing Bernard's characterization of the *internal environment* as the "totality of the circulating fluids of the organism," Cannon, 1932 p. 38). This matrix includes blood and lymph, and some of its features to be maintained are temperature, pressure, and concentrations of ions and molecules. Although Cannon described other means of maintaining homeostasis such as buffering, his main examples involved negative feedback. By this time human designers had identified negative feedback as an effective means of maintaining mechanical systems in a constant target state. Subsequently negative feedback was adopted by the cyberneticists as providing a primary means for controlling biological, social, and engineered systems (Wiener, 1948). For many, homeostasis became identified with negative feedback.

Negative feedback provides a useful starting place for understanding how local control can help maintain the organism. Negative feedback involves measuring a product produced by a production mechanism and, if the value falls outside a target range, acting on one or more constraints in the producing mechanism to alter its function. For example, if pancreatic β cells detect that glucose levels in the blood exceeds a target, they increase the synthesis of insulin and release massive amounts of it into the blood, where it can bind receptors on different cell types. When this high amount of insulin binds to receptors on liver cells, it speeds up glucose intake and the process in which glucose is converted to glycogen, thereby reducing the concentration of glucose in the blood. This process stops when blood glucose concentrations drop below the level that stimulates high insulin release.

In many circumstances, local negative feedback control of individual production mechanisms can provide a relatively constant environment. But it has its limits. To the degree that an organism has stored glycogen, negative feedback can restore glucose levels when they drop too low. This is achieved by releasing glucagon from pancreatic α cells, which stimulates gluconeogenesis from glycogen. But over time the supply of glycogen will be exhausted, and the organism must procure additional nutrients if it is to maintain sufficient glucose levels to fuel the organism's production and control mechanisms. This requires control processes that initiate other activities such as those involved in feeding. For this, mammals rely on other hormones, for example ghrelin and leptin, being transported to the arcuate nucleus of the hypothalamus, a location in the brain without a blood-brain barrier at which hormones can act on the receptors of neurons. Ghrelin signals lack of food in the digestive system while leptin signals presence of fat. By measuring these and other physiological states of the organism and integrating them, neurons in the arcuate nucleus detect the need for eating and signal to neurons elsewhere in the hypothalamus act to initiate feeding activities.

The hypothalamus consists of multiple nuclei each comprising different populations of neurons, many of which respond to endocrines and are involved in releasing endocrines as well as neurotransmitters. Moreover, they often signal to each other with peptides or neuroendocrines, which are also distributed through the extracellular matrix. Some of these neurons, such as those that respond to ghrelin and leptin in the arcuate nucleus, are specialized for one type of activity (registering hunger or satiety in the case of agouti-related protein expressing neurons and pro-opiomelanocortin expressing neurons respectively). But cells in other nuclei, such as the lateral hypothalamus (one of the sites to which neurons in the arcuate nucleus signal) receive multiple signals and send multiple outputs. The orexin neurons provide an illustrative example. They were so named after the Greek word for appetite since they were first identified as promoting eating activities (Sakurai et al., 1998). But they were subsequently implicated in an animal transitioning from sleep to waking (Adamantidis et al., 2007). Tsunematsu et al. (2013) showed that silencing them sufficed to induce slow wave sleep. Orexin neurons illustrate a common theme exemplified by many nuclei in the hypothalamus and other brain regions—they integrate signals from multiple sources and send signals (chemical and electrical) to multiple other centers, some leading to action (Fig. 5.3). The result is that control mechanisms regulating individual production mechanisms are coupled together so that information procured to control one production mechanism is also employed to control other production mechanisms. Accordingly, control of individual production mechanisms takes into account a wide range of conditions in the organism. This appears to be a mode of heterarchical organization that is effective in enabling organisms to maintain themselves.

By starting with negative feedback, we have treated control as a reactive process—each negative feedback control mechanism begins with measuring conditions and responding to that information. Even when these are integrated, the process starts with measuring a condition in the organism or its environment. But control mechanisms are capable of anticipatory control as well: they can enable an

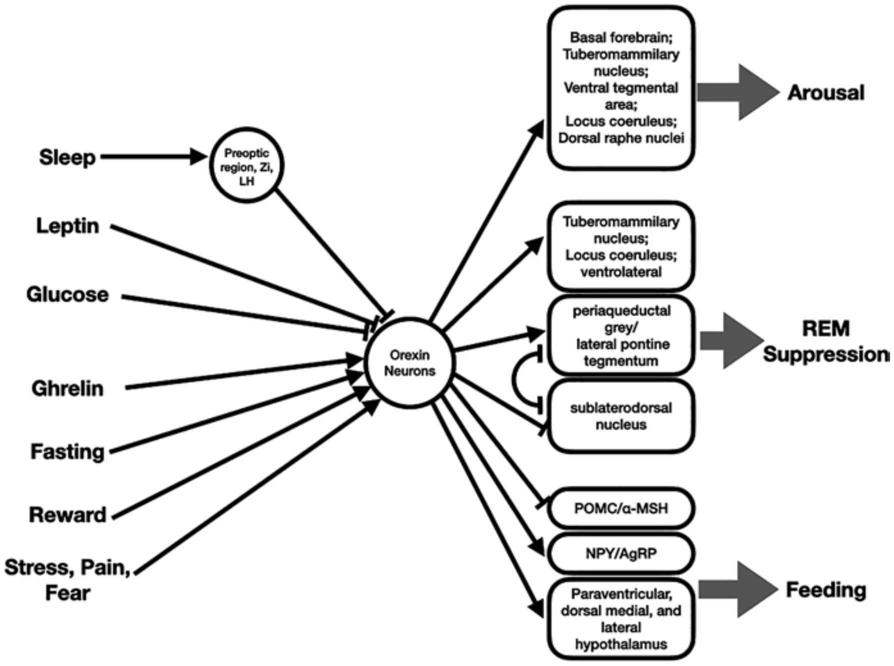

Fig. 5.3 Orexin neurons in the lateral hypothalamus respond to signals released by multiple other control mechanisms and have effects on multiple behaviors. (Based on data in Arrigoni et al. (2019))

organism to regulate its production mechanisms so that they operate in ways appropriate for conditions the organism is likely to confront in the future. For example, an organism's environment regularly presents different conditions at different times of day and, except in the tropics, during different seasons of the year. Controlling production mechanisms in ways that anticipate these conditions is facilitated by another nucleus in the hypothalamus, the suprachiasmatic nucleus (SCN), which generates oscillations with a period of approximately 24 hours (hence, circadian). Both through electrical signaling and release of peptides, neurons in the SCN send signals that are responded to either directly by production mechanisms or by neurons controlling other production mechanisms. The circadian system enables organisms to anticipate events that have occurred in a regular fashion over the phylogeny of the organism (Moore-Ede, 1986). Associative learning, achieved by changing constraints in neuroreceptors, provides a means to modulate control activities in light of regularities experienced by an organism in its lifetime. By modifying the constraints within neurons that determine how they integrate information to control various activities, neurons in nuclei in the hypothalamus and other brain regions enable organisms to initiate activities appropriate to events that are likely to follow. Accordingly, control mechanisms can be both reactive and anticipatory.

What this brief consideration of the hypothalamus suggests is that the control mechanisms that enable organisms to maintain themselves are often specific to the production mechanism being controlled. When coordination of control mechanisms is required, different control mechanisms interact with each other so that measurements procured in the control of one activity can also modulate the control of other activities. Control mechanisms do operate on other control mechanisms, but rather than assuming control over subordinates, these control mechanisms integrate multiple measurements and, based on the result, modify constraints in the more local control mechanisms. Often the control needed to maintain the organism involves locomotor activity that procures food or avoids dangerous situations. There is not space to develop the account here, but this involves the control of skeletal muscles. Here too control is primarily specific to the production mechanism. Individual muscles are controlled by pattern generators which are then coupled to enable multiple muscles to coordinate their contraction. The activity of these pattern generators can be modulated by signals not only from other pattern generators but also by those from neurons in different nuclei of the hypothalamus or other brain regions that register conditions requiring behavioral adjustment.

Of particular significance in coordinating different production mechanisms are the so called neuromodulators—transmitters such as dopamine, serotonin, and numerous neuropeptides. In response to measured conditions in the organism, these neurotransmitters are released into extracellular space and diffuse to neurons with appropriate receptors. They act on a relatively long timescale (e.g., seconds and minutes), transforming the context in which other neural processing occurs. Due to the extended space and time in which they act, they can modulate the behavior of many specific controllers (Katz, 1999). Despite their importance in directing overall activity both in the brain and the organism, neuromodulators do not instantiate a hierarchical system. Each is released by different nuclei in the brain and promotes different activities. The control they execute is heterarchical (Bechtel, 2022). When there are conflicts, the determination as to which activities to carry out is made by another set of nuclei, those of the basal ganglia. These nuclei enable a competition between control mechanisms, inhibiting all but the winner of the competition, thereby avoiding conflicts between them (Bogacz & Gurney, 2007). However, the basal ganglia are not themselves in control—they are simply another component in a heterarchically organized network of control mechanisms (Bechtel & Huang, 2020).

Taking our cue from mammals, we see that the control mechanisms that serve to maintain organisms are organized heterarchically, not hierarchically, with much control remaining specific to the production mechanisms being controlled. When it is important to coordinate multiple responses, control mechanisms are employed that integrate multiple control mechanisms. Of course in mammals these control processes are supplemented with other control mechanisms such as those in the neocortex. The distinctive potency of neocortical processing is exhibited in visual processing. Whereas many vertebrates rely primarily on the tectum/superior colliculus to coordinate visually acquired information directly with motor activity, by relying on the neocortex, higher mammals can engage in more complex categorization and learning in response to visual inputs. But, as illustrated by the ability of decerebrate cats to live on their own, albeit in protected environments (Bjursten et al., 1976), cortical processing is not required for many of the activities organisms perform in the service of their self-maintenance. Moreover, when processing is carried out in the neocortex, it must be coupled with the more basic control mechanisms on which we have focused in order to affect behavior Sub-cortical control mechanisms are fundamental to the ability of organisms, including humans, to maintain themselves.

5.6 Conclusions

Organisms need mechanisms to construct, repair, and maintain themselves. A major difference between human-made machines and biological mechanisms is that biological mechanisms are dependent on the organism of which they are part to construct, maintain, and repair them. Organisms and biological mechanisms are mutually dependent: without the organism, biological mechanisms wouldn't exist and endure; without mechanisms, the organism would not maintain itself. Our contention has been that this mutual dependence is mediated by control mechanisms. Without control mechanisms, production mechanisms will simply carry out their activities any time what Machamer et al. call start or set-up conditions are satisfied. They won't tailor their activities to what the organism needs to maintain itself. Only if production mechanisms are controlled will they perform their activities when and in the manner needed to maintain the organism.

Our discussion of control mechanisms reveals two complementary features. On the one hand, the constraints constituting control mechanisms are the product of the mechanisms that constitute the organism. On the other hand, the particular values they take are determined by the measurements they make. By measuring appropriate variables, control mechanisms are able to act on production mechanisms so that they serve the needs of the organism. This very ability, though, is determined by how they are constituted by other mechanisms in the organism. They are thereby part of the closure of constraints but also open to the information that is relevant to whether the actions of production mechanisms are needed and useful to the organism.

We have emphasized that organisms exhibit a multitude of control mechanisms. If they are the basis for organisms successfully maintaining themselves, their activity needs to be coordinated. Although hierarchical organization would ensure coherence, we have argued that in biological systems control is organized heterarchically. Inspired by biology, we suggest that effective heterarchical control involves controllers of specific mechanisms being integrated into networks in which information procured by different control mechanisms is shared and used to constrain the behavior of the different control components. Such heterarchical networks, crafted over the course of evolution, appear to be what enable organisms to maintain themselves while engaging dynamic environments.

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