5 Physicalism, Chaos and Reductionism

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Summary. In addition to ignoring the severe practical problems posed by decoherence phenomena, quantum mind hypotheses are motivated by a misunderstanding of the nature of classical (i. e. nonquantum) dynamics. As presently understood, nonlinear dynamical systems – of which the brain is clearly one – exhibit the twin phenomena of chaos and emergence. The first of these impedes reductionist formulations as does quantum theory, and the second leads to hierarchical structures in biological organisms and cognitive systems, which are difficult to analyze reductively. Thus a quantum mind theory must rest on empirical evidence rather than philosophical speculation.

5.1 Introduction

Although it is suggested in other chapters of this book that quantum phenomena play important roles in neuroscience, arguments to the contrary are compelling [30]. Due to a disruptive process called decoherence, a large-scale quantum state in a biological brain would become disorganized by random thermal motions in a very short time, leaving a system that can be accurately described by classical dynamics, as is widely assumed by the neuroscience community [26].

One of the reasons that supporters of “quantum mind” hypotheses advance for assuming that quantum theory must play a key role in neuroscience – I suspect – is philosophical. Classical dynamics seems to imply that high-level brain processes can be reduced, in principle if not in practice, to a description that is based on the classical laws of physics and chemistry, leaving no room for the subjective experiences that we confirm in our daily lives. To avoid this unwelcome conclusion, it is asserted that quantum theory must be an essential component in the dynamics of biological brains, and various arguments are advanced to show that large-scale quantum states can indeed survive long enough to play functional roles in living organisms.

The primary aim of this chapter is to show that classical neuroscience cannot be reduced to fundamental descriptions; thus quantum theory is not needed to provide theoretical space for those phenomena that we know exist but don’t understand.

The chapter opens with a brief review of the basic facts of quantum decoherence and an introduction to current perspectives on classical nonlinear dynamics, including the concept of emergence. It is then shown that we humans are exceptionally intricate organisms with many levels of functional activity, some biological and others cognitive. In other words, we comprise both a biological hierarchy and a cognitive hierarchy, both governed by nonlinear dynamics. Under the assumption of physicalism, arguments supporting the concept of reductionism are presented as a prelude to a survey of its problematic aspects. Among these are the immense numbers of higher-order structures that can emerge at each level of the biological and cognitive hierarchy, and the phenomenon of dynamical chaos that leads to the "butterfly effect" (formally termed a "sensitive dependence on initial conditions"). The nature of causality is then considered from an Aristotelian perspective, recognizing how complicated this notion can be in the context of nonlinear systems. Finally, the concept of downward causation is introduced, which leads to the emergence of intricate networks of positive feedback in open systems. As these networks can span many levels of both the biological and cognitive hierarchies, ample scope for challenging the claims of reductionism become apparent.

5.2 Quantum and Classical Dynamics

The dynamics of atomic particles are necessarily described by quantum theory because these particles also exhibit wave properties. As was first proposed by Louis de Broglie in his 1924 doctoral thesis and soon confirmed experimentally, an electron has a wavelength equal to Planck's constant (h) divided by its momentum (mass times velocity). De Brolie's suggestion inspired Erwin Schrödinger to formulate his famous wave equation, which provides a theoretical basis for chemical bonding among many important applications. Yet the particles that we deal with in our daily lives (golf balls, for example) do not exhibit wave properties – they are entirely particle-like in nature. How can we decide whether to use quantum or classical mechanics to study a particular problem?

In considering the relevance of quantum phenomena at a temperature (T), an important number to keep in mind is the *thermal de Broglie wavelength*

$$\lambda_{\mathrm{T}} = \frac{h}{\sqrt{2mkT}} , \tag{5.1}$$

which is the wavelength of a particle that is moving with thermal velocity. (In this equation, k is the Boltzmann constant, which indicates the thermal energy per unit of absolute temperature.) Notice that as the temperature and particle mass (m) increase, λ_{T} gets smaller. For a sufficiently large product of mass and temperature, $\lambda_{\mathrm{T}} \ll \Delta x$ (where Δx is the precision to which the particle position is carried in measurements or theoretical analyses), and the results of quantum calculations will be identical to those of nonlinear classical (nonquantum) calculations.

Consider a golf ball, which according to international agreement has a mass of 45.9 g. At 300 K, a golf ball has a thermal de Broglie wavelength of $\lambda_\mathrm{T} = 3.4 \times 10^{-23}$ m, which is many orders of magnitude smaller than the size of an atomic nucleus and so far smaller than any conceivable Δx. Thus there is no point in using quantum theory to describe a golf ball as it sits on a tee, moving about with random thermal motion while waiting to be struck. After it is struck and is soaring down the fairway, the wavelength of a golf ball is even smaller, and quantum theory is even less relevant. Suppose we ignore this insight and ask how long an initially constructed quantum state can exist before being scattered by the myriad influences of random thermal vibrations. The time scale on which an initial quantum state decays into a corresponding classical description is called the *decoherence time* (τ_D), and Wojciech Zurek has shown that [37]

$$\tau_\mathrm{D} \sim \tau_\mathrm{R} \left(\frac{\lambda_\mathrm{T}}{\Delta x} \right) , \tag{5.2}$$

where τ_R is the time scale for corresponding classical processes and Δx can be interpreted as the distance between two virtual locations of the particle. Evidently, the condition $\lambda_\mathrm{T} \ll \Delta x$ implies $\tau_\mathrm{D} \ll \tau_\mathrm{R}$, which means that classical processes dominate the dynamics.

Returning to our golf ball and taking Δx to be about the size of an atom (10^{-10} m), we see that any initial quantum state would decay (decohere) into a corresponding classical state in about 10^{-13} times the classical time constant, rendering meaningless any quantum corrections to the classical formulation.

To show how well the electrodynamics of neuroscience can be described in classical terms, Max Tegmark has recently estimated the decoherence time in biological brains under a variety of assumptions, finding that $\tau_\mathrm{D} \sim 10^{-13}$ to 10^{-20} s [30], which is many orders of magnitude less than the times that are empirically relevant [26]. Thus – as with the golf ball – the classical representation of dynamic variables in neuroscience is on a firm theoretical footing: adding quantum corrections won't tell us anything.

To see how classical dynamics are able to represent the strongly nonlinear phenomena observed in biological brains, we shall assume in the following discussion that quantum effects can be neglected and see what difficulties and opportunities arise.

5.3 What Are Classical Nonlinear Phenomena?

The short answer to this question – suitable for a cocktail party response – is that nonlinear phenomena are those for which the whole is greater than the sum of its parts. Going beyond this slogan, one can point to an impressive array of dynamic effects currently studied under the aegis of nonlinear science, including but not limited to the following:

- *emergent structures* (tornadoes, tsunamis, lynch mobs, optical solitons, black holes, schools of fish, cities, Jupiter's Great Red Spot, nerve impulses)
- *filamentation* (rivers, bolts of lightning, woodland paths, optical filaments)
- *chaos* (sensitive dependence on initial conditions or the "butterfly effect", strange attractors, Julia sets, turbulence)
- *threshold phenomena* (an electric wall switch, the trigger of a pistol, flip-flop circuits, tipping points, the all-or-nothing property of a neuron)
- *spontaneous pattern formation* (natural languages, fairy rings of mushrooms, the Gulf Stream, fibrillation of heart muscle, ecological domains)
- *harmonic generation* (digital tuning of radio receivers, conversion of laser light from red to blue, musical overtones)
- *synchronization* (Huygens's pendulum clocks, electric power generators connected to a common grid, circadian rhythms, hibernation of bears, flashing of Indonesian fireflies, human empathy), and
- *shock waves* (sonic booms of jet airplanes, the sound of a cannon, bow waves of a boat, sudden pileups in smoothly flowing automobile traffic)

For a broad view of this area, see the recently published *Encyclopedia of Nonlinear Science* [29]. All of these striking phenomena and more can play roles in the nonlinear dynamics of hierarchical systems.

A yet deeper answer to the above question recognizes that the definition of nonlinearity involves a statement about the nature of causality. This perspective is presented below after we look at the hierarchical nature of living organisms.

5.4 The Biological and Cognitive Hierarchies

Before taking up philosophical issues, consider the following biological hierarchy of a living organism.

Biosphere
Species
Organisms
Organs
Cells
Processes of replication
Genetic transcription
Biochemical cycles
Biomolecules
Molecules

In thinking about this formulation, five comments are appropriate.

First, it is only the general nature of the hierarchy that is of interest to us here, not the details. One might include fewer or more levels in the diagram or account for branchings into (say) flora and fauna or various phyla. Although such refinements may be useful in particular discussions, the present aim is to study the general nature of a nonlinear dynamic hierarchy, so a relatively simple diagram is appropriate.

Second, the nonlinear dynamics at each level of description generate emergent structures, and nonlinear interactions among these structures provide a basis for the dynamics at the next higher level [27].

Third, the emergence of new dynamic entities stems from the presence of closed causal loops, in which positive feedback leads to exponential growth that is ultimately limited by nonlinear effects.

Fourth, these closed causal loops also provide a basis for the phenomenon of dynamical chaos, fortuitously discovered by the eminent French mathematician Henri Poincaré near the end of the nineteenth century. In his words [24]:

> "If we knew exactly the laws of nature and the situation of the universe at the initial moment, we could predict exactly the situation of that same universe at a succeeding moment. But even if it were the case that the natural laws had no longer any secret for us, we could still only know the initial situation approximately. If that enabled us to predict the succeeding situation with the same approximation, that is all we require, and we should say that the phenomenon had been predicted, that it is governed by laws. But it is not always so; it may happen that small differences in the initial conditions produce very great ones in the final phenomena. A small error in the former will produce an enormous error in the latter. Prediction becomes impossible, and we have the fortuitous phenomenon."

The possibility of such fortuitous phenomena was largely ignored by the scientific world until the 1960s, when a clear example was observed numerically by an MIT meteorologist named Edward Lorenz. He was using the newly available digital computer to develop atmospheric models for weather prediction – a challenging task.

At the outset of a difficult study, scientists often consider simple versions of their real problems, but even after paring his model down to only three dynamic variables, Lorenz found a geometric growth of small errors, just as Poincaré had theoretically predicted for errors in the three-body problem of planetary motion. Weather prediction beyond a certain limited time was thus shown to be impossible, a result that Lorenz emphasized in a 1972 talk famously entitled: "Predictability: Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?"

Thus the term "butterfly effect" entered our language as a graphic metaphor for Poincaré's fortuitous phenomenon, but the concept of a sharp division between possible futures is much older; in geography there is a divide (or watershed), where water runs either east to one sea or west to another, and in mathematics, such a sharp dividing line is called a separatrix. Less formally, politicians and social scientists speak of a "tipping point" and of the "straw that broke the camel's back", and we are all familiar with a light switch – which is either on or off – and a coin toss. Such switches are the essential elements of modern electronics, and a computer can be viewed as a system of many interconnected switches. Some believe that the human brain can be similarly described as it parses the future in unanticipated ways.

Finally, the number of possible entities that can emerge at each level is immense, implying that all possibilities cannot be physically realized in a finite universe. Thus only a small subset of the possible emergent and chaotically interacting entities actually occur.

In addition to the biological hierarchy, each of us also comprises a cognitive hierarchy with the following structure.

Human culture
Phase sequences
Complex assemblies
. . .
. . .
Assemblies of assemblies of assemblies
Assemblies of assemblies
Assemblies of neurons
Neurons
Nerve impulses
Nerve membranes
Membrane proteins
Molecules

Although this diagram differs from the biological hierarchy in some ways, the previous comments apply. In particular, each cognitive level has its own nonlinear dynamics, involving closed causal loops of positive feedback, out of which can emerge an immense number of chaotically interacting entities. A necessarily small subset of these possibilities does in fact emerge, providing a basis for the nonlinear dynamics of the next higher level.

Perhaps the most significant difference between the biological and cognitive hierarchies stems from the internal levels, which involve assemblies of neurons described by Donald Hebb as follows [16–18].

> "Any frequently repeated, particular stimulation will lead to the slow development of a 'cell-assembly,' a diffuse structure comprising cells . . . capable of acting briefly as a closed system, delivering facilitation to other such systems and usually having a specific motor facilitation. A series of such events constitutes a 'phase sequence' – the thought process."

Because an assembly shares the threshold (all-or-nothing) properties of individual neurons, this concept is hierarchical. Thus these internal levels range from assemblies of neurons to the phase sequence, but their existence is deduced from theoretical speculation and circumstantial evidence rather than direct observation [26].

Importantly, philosophers disagree about the ontological nature of emergent entities. Do the various levels of the biological and cognitive hierarchies differ merely by their labels, convenient for academic organization, or are some of them qualitatively different aspects of reality? In attempting to answer this question, it is necessary to understand how the upper levels are related to lower levels, which brings us to the doctrine of reductionism.

5.5 Reductionism

Since the seventeenth century, the reductive program has been surprisingly successful in prising out explanations for the behavior of the natural world. This perspective is now widely accepted by the scientific community as the fundamental way to pose and answer questions. Basically, the reductive approach to understanding natural phenomena proceeds in three steps.

- *Analysis.* Assuming some higher-level phenomenon is to be explained, separate the dynamics of that phenomenon into components, the behaviors of which are individually investigated.
- *Theoretical formulation.* Guided by empirical studies and imagination, develop a theoretical formulation of how the components interact.
- *Synthesis.* In the context of this formulation, derive the higher-level phenomenon.

Among the many aspects of nature that have fallen to this approach, one can mention planetary motion (based on the concepts of mass and gravity and on Newton's laws of motion), electromagnetic radiation (based on the concepts of electric charge, electric fields, and magnetic fields related through Maxwell's electromagnetic equations), atomic and molecular structures (based on the concepts of mass, electric charge, Planck's constant, and Schrödinger's equation for the dynamics of quantum probability amplitudes), and nerve impulse propagation (based on the concepts of voltage, membrane permeability, ionic current, and the Hodgkin–Huxley equations for the dynamics of current flow through a voltage-sensitive membrane).

Generalizing from such specific examples, some believe that all natural phenomena can be understood in this way [33]. Others maintain that there exist natural phenomena that cannot be completely described in terms of lower-level entities – life and the human mind being outstanding examples. In its more extreme form, this latter position is called substance dualism: the view of René Descartes that important aspects of the biological and cognitive realms do not have a physical basis. A less extreme position is property dualism, which accepts a physical basis but asserts aspects of biology and social science that cannot be explained in terms of atomic or molecular dynamics. Under property dualism, higher-level phenomena are thought to be divided between those that can be understood and explained in terms of physics and chemistry and those that cannot.

To statements of belief there is no scientific response, but if we can agree on the physical basis of life and mind, the scope of the discussion narrows. Let us agree, therefore, that all biological and mental phenomena supervene on the physical in the following sense. If the constituent matter is removed, the phenomenon in question disappears, or as philosopher Jaegwon Kim puts it in the context of cognitive phenomena [20]: "Any two things that are exact physical duplicates are exact psychological duplicates as well." This position is called physicalism, and among biologists it is now widely accepted for the phenomenon of life. In other words, there is no Bergsonian "life force" or elan vital that exists independent of the molecules comprising a living organism. Simarly, most neuroscientists believe that a person's mind (or consciousness) would not survive removal of the molecules of his or her brain. Under this assumption, two questions arise.

- Does reductionism follow from physicalism?
- Does physicalism allow property dualism?

Over the past two decades, these questions have been considered by Kim [20], who reluctantly concludes that physicalism does indeed imply reductionism and sits uneasily with property dualism. Let us review his argument with reference to Fig. 5.1.

This figure represents higher-level mental phenomena (M_1 and M_2) that supervene on lower-level physical descriptions (P_1 and P_2), where supervenience is indicated by the vertical dashed lines. In other words, if the properties P_1 are removed, then the phenomenon M_1 will disappear, with a similar relationship between P_2 and M_2.

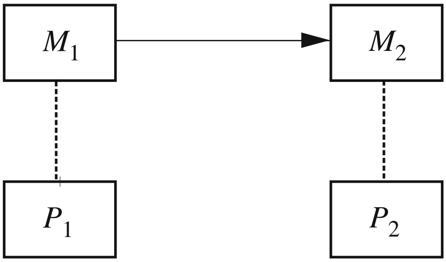

Fig. 5.1. The causal interaction of higher-level phenomena (M_1 and M_2) that supervene on lower-level properties (P_1 and P_2)

Now suppose that studies in experimental psychology have established a causal relationship between M_1 and M_2 (indicated by the horizontal arrow in Fig. 5.1), under which the initial upper-level observation of M_1 always leads to a corresponding upper-level observation of M_2. Because under the assumption of physicalism P_1 (P_2) must be present to provide a basis for M_1 (M_2), we could as well say that P_1 causes P_2, which is a formulation of the upper-level causality in terms of the corresponding lower-level properties. In other words, one could reduce the causal relation between phenomena M_1 and M_2 to a corresponding relation between P_1 and P_2, thereby supporting reductionism and undercutting property dualism. There is no claim that this reduction is convenient or even feasible, but that it is possible "in principle".

In addition to this logic, there is a practical argument for the reductive view. Even if reductionism were not to hold for all aspects of biological or mental organization, it is still a prudent strategy for the majority of biologists and cognitive scientists to take as a working hypothesis. Why? Often the riddles of one generation become standard knowledge of the next; thus the dualist (substance or property) is ever in danger of giving up too soon on the search for reductive formulations. One might say that it is the duty of a scientist to search for reductive explanations of natural phenomena.

5.6 Objections to Reductionism

As we have seen, reductionism based on physicalism is a serious philosophical position meriting careful response. Those who disagree on intuitive grounds must offer substantial objections. Let us consider some.

5.6.1 Constructionism versus Reductionism

Although many elementary particle physicists (often those who seek a "theory of everything") are reductionists [33], condensed-matter physicists (who study aggregates of atoms and molecules) tend to question such claims. Thus Philip Anderson has asserted [2]:

> "The reductionbist hypothesis does not by any means imply a 'constructionist' one: The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. In fact the more the elementary-particle physicists tell us about the nature of the fundamental laws, the less relevance they seem to have to the very real problems of the rest of science, much less to those of society. The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity."

What is it about "scale and complexity" that creates problems for the constructionist hypothesis?

5.6.2 Immense Numbers of Possibilities

Severe computational difficulties arise in life science because the number of possible emergent structures at each level of the biological hierarchy (although finite) is too large to be counted. To sharpen such ideas in theoretical biology, physicist Walter Elsasser introduced the term *immense* to characterize a number that is finite but greater than a *googol* (10^{100}), and thus is inconveniently large for numerical studies [7, 9].

To grasp Elsasser's concept, consider the proteins. These workhorses of biochemistry are valence-bonded strings of amino acids, each designated by an underlying DNA code. Because there are 20 different amino acids and a typical protein is composed of some 200 of them, the number of possible proteins is about 20^{200}, which is greater than a googol. As the number of possible proteins grows very rapidly with the length of the amino-acid string, mathematicians call this a "combinatorial explosion."

The number of possible protein molecules is therefore immense, meaning that all the matter in the universe falls far short of that required to construct but one example of each possible protein molecule [9, 25]. Throughout the eons of biological evolution, most of the possible protein molecules have never been constructed and never will be. Those particular proteins that are presently known and used by living creatures were selected in the course of evolution through a succession of historical accidents that are consistent with the laws of physics and chemistry but not determined by them.

So it goes at all levels of the biological and cognitive hierarchies. Combinatorial explosions abound, and the number of entities that might emerge from each hierarchical level – to form a basis for the dynamics of the next level – is immense, suggesting that happenstance guides the evolutionary process [15].

It follows that biological science differs fundamentally from physical science, which deals with homogeneous sets having identical elements. Thus a physical chemist has the luxury of performing as many experiments as are needed to establish laws governing the interactions among (say) atoms of carbon and hydrogen as they form molecules of benzene. In the biological, cognitive, and social sciences, on the other hand, the numbers of possible members in most interesting sets are typically immense, so experiments are necessarily performed on heterogeneous subsets of the classes of interest. Because the elements of heterogeneous subsets are never exactly the same, it follows that experiments cannot be precisely repeated. Thus causal laws cannot be determined with the same degree of certainty in the biological, cognitive and social sciences as in the physical sciences.

In other words, psychologists establish rules rather than laws for interpersonal interactions, and your doctor can only estimate the probability that a certain pill will cure you. At the levels of biology, neuroscience, and social science, therefore, the horizontal arrow from M_1 to M_2 in Fig. 5.1 should better be drawn fuzzy or labeled with an estimate of its reliability, to indicate this deviation from strict causality.

5.6.3 Sensitive Dependence on Initial Conditions

Nonlinear dynamics offer many examples of the sensitive dependence on initial conditions, leading to the "fortuitous phenomena" noted by Poincaré and dubbed "the butterfly effect" by Lorenz, but such effects have long been informally recognized. Among computer engineers and neuroscientists, the corresponding idea of a threshold level at the input of an information processor – below and above which different outcomes transpire – is an essential concept.

In neuroscience, threshold phenomena are becoming increasingly important. Although the linear dendritic dynamics assumed for neurons until the 1980s helped the analyst follow the strands of theoretical causality, real dendrites are now known to be highly nonlinear, offering many additional tipping points to the dynamics of every neuron [26]. How are these twisted skeins of causality to be sorted out?

5.6.4 The Nature of Causality

Whether one is concerned with establishing dynamic laws in the physical sciences or seeking rules in the biological and social sciences, the notion of causality requires careful consideration [6]. As was noted above, a study of causality is essential for appreciating nonlinear phenomena, but it is not a new issue. Some twenty-three centuries ago, Aristotle noted that "We have to consider in how many senses because may answer the question why" [3]. As a "rough classification of the causal determinants of things," he suggested four types of causes.

- *Material cause.* Material cause stems from the presence of some physical substance that is needed for a particular outcome. Aristotle suggested that bronze is an essential factor in the making of a bronze statue, but the concept is more general. Obesity in the United States, for example, is materially caused by the overproduction of corn (maize), just as Russian alcoholism is materially caused by the abundance of vodka.
- *Formal cause.* The material necessary for some particular outcome must be available in the appropriate form. The blueprints of a house are necessary for its construction, the DNA sequence of a particular gene is required for synthesis of the corresponding protein, and a pianist needs the score to play a concerto.
- *Efficient cause.* For something to happen, according to Aristotle, there must be an "agent that produces the effect and starts the material on its way." Thus, a golf ball moves through the air in a certain trajectory because it was struck at a particular instant of time by the head of a club. Similarly, a radio wave is emitted into the ether in response to the current that is forced to flow through an antenna. Following Galileo, this is the standard sense in which physical scientists use the term causality [6].

- *Final cause.* Events may come about because they are desired by some intentional organism. Thus a house is built – involving the assembly of materials, reading of plans, sawing of wood, and pounding of nails – because someone wishes to have shelter from the elements. Such purposive answers to the question “why?” are problematic in the biological sciences, and they emerge as central issues at upper levels of the cognitive hierarchy.

For those familiar with the jargon of mathematics, the following paraphrasing of Aristotle’s definitions may be helpful.

- At a particular level of the biological hierarchy, a material cause might be a time or space average over dynamic variables at lower levels of description and enter a hierarchical formulation as a slowly varying parameter at the level of interest.
- Again, at a particular level of the biological hierarchy, formal causes might arise from the more slowly varying values of dynamic variables at higher levels of description, which enter as boundary conditions at the level of interest.
- An efficient cause is represented by a stimulation–response relationship, which is usually formulated as a differential equation with a dependent variable that responds to a forcing term. Fledgling physical scientists spend their formative years solving such problems, with the parameters (material causes) and boundary conditions (formal causes) specified. This educational experience may explain why physical scientists tend to assume that everything that transpires in nature can be described in terms of efficient causes.
- In mathematical terms, it is not clear (to me, at least) how one might formulate a final cause.

Although this classification seems tidy, reality is usually more intricate. Thus Aristotle noted that causes may be difficult to sort out in particular cases, with several of them often “coalescing as joint factors in the production of a single effect” [3]. Such interactions among component causes are a key property of nonlinear phenomena.

Distinctions among Aristotle’s “joint factors” are not always easy to make. A subtle difference between formal and efficient causes appears in the metaphor for Norbert Wiener’s cybernetics: the steering mechanism of a ship [34]. If the wheel is connected directly to the rudder (via cables), then the forces exerted by the helmsman’s arms are the efficient cause of the ship executing a change of direction. For larger vessels, however, control is established through a servomechanism in which the position of the wheel merely sets a pointer that indicates the desired position of the rudder. The forces that move the rudder are generated by a feedback control system (or servomechanism) that minimizes the difference between the actual and desired positions of the rudder. In this case, one might say that the position of the pointer is a formal cause of the ship's turning, with the servomotor of the control system acting as the efficient cause.

Another example is provided by the conditions needed to cause the firing of a neuron. If the synaptic weights and firing threshold are supposed to be constants, they can be viewed as formal causes of a firing event. On a longer time scale associated with learning, however, these parameters can be viewed collectively as a weight vector that is governed by the learning dynamics and might be classified as efficient causes of neuron ignition. Although the switching of a real neuron is far more intricate than this simple picture suggests, the point remains valid – neural switching is a nonlinear dynamic process, melding many contributing factors.

Finally, when a particular protein molecule is constructed within a living cell, sufficient quantities of appropriate amino acids must be available to the messenger RNA as material causes. The DNA code, controlling which amino acids are to be arranged in what order, is a formal cause, and the chemical (electrostatic and valence) forces acting among the constituent atoms are efficient causes.

For applied mathematicians, it is not surprising to find several different types of causes involved in a single event. We expect that parameter values, boundary conditions, and forcing functions will all combine to influence the outcome of a given computation. What other complications of causality are anticipated?

5.6.5 Nonlinear Causality

In applied mathematics, the term "nonlinear" is defined in the context of relationships between efficient causes and effects. Suppose that a series of experiments on a certain system have shown that cause C_1 gives rise to effect E_1; thus

$$C_1 \to E_1 \,,$$

and similarly

$$C_2 \to E_2$$

expresses the relationship between cause C_2 and effect E_2. This relation is *linear* if

$$C_1 + C_2 \to E_{12} = E_1 + E_2 \,. \tag{5.3}$$

If, on the other hand, E_{12} is not equal to $E_1 + E_2$, the effect is said to be a *nonlinear* response to the cause.

Equation (5.3) indicates that for a linear system any efficient cause can be arbitrarily divided into components $(C_1, C_2, \ldots, C_n)$, whereupon the effect will be correspondingly divided into $(E_1, E_2, \ldots, E_n)$. Although convenient for analysis – providing a basis for Fourier analysis and Green function methods – this property is not usually found in the realms of biological, cognitive, and social sciences [25, 27, 29].

Far more common is the nonlinear situation, where the effect from the sum of two causes is not equal to the sum of the individual effects. The whole is not equal to the sum of its parts. Nonlinearity is less convenient for the analyst because multiple causes interact among themselves, allowing possibilities for many more outcomes, obscuring relations between cause and effect and confounding the constructionist. For just this reason, nonlinearity plays a key role in the course of biological evolution and the organization of the human mind.

5.6.6 The Nature of Time

Causality is intimately connected with the way we view time – thus, the statement "C causes E" implies (among other things) that E does not precede C in time [6] – yet the properties of time may depend on the level of description [12, 13, 35, 36]. Thus, the dynamics underlying molecular vibrations are based on Newton's laws of motion, in which time is bidirectional. In other words, the direction of time in Newton's theoretical formulation can be changed without altering the qualitative behavior of the system. At the level of a nerve impulse, on the other hand, time is unidirectional, with a change in its direction making an unstable nerve impulse stable and vice versa. In appealing to Fig. 5.1, therefore, the reductionist must recognize that the nature of the time used in formulating the causal relationship between P_1 and P_2 may differ from that relating M_1 and M_2.

5.6.7 Downward Causation

Reductionism assumes that causality acts upward through the biological hierarchy, where the causality can be interpreted as both efficient and material. Formal causes, on the other hand, can also act downward because variables at the upper levels of a hierarchy can place constraints (boundary conditions, for example) on the dynamics at lower levels [1].

A dramatic example of downward causation occurred eons ago when certain bacteria began to harvest and store energy from the sun, creating atmospheric oxygen as a poisonous waste [22]. The presence of oxygen in the atmosphere, in turn, led to the emergence of the animal kingdom, in which we humans participate. Other examples of downward causation include modifications of DNA codes caused by interactions among species, germination of an ovum following sexual activity, and the disintegration of an organism upon death.

Although such examples provide convincing evidence of downward causation, the means through which it acts are not widely understood. To sort things out, Claus Emmeche and his colleagues have recently defined three types of downward causation [10].

- *Strong downward causation* (SDC). Under SDC, it is supposed that upper-level phenomena can act as efficient causal agents in the dynamics of lower levels. In other words, upper-level organisms can modify the physical and chemical laws governing their molecular constituents. Presently, there is no empirical evidence for the downward action on efficient causation, so SDC is almost universally rejected by biologists.
- *Weak downward causation* (WDC). WDC assumes that the molecules comprising an organism are governed by some nonlinear dynamics in a phase space, having attractors (which include the living organism) each with a corresponding basin of attraction. Under WDC, a higher-level phenomenon might move certain lower level variables from one basin of attraction to another. With this formulation, for example, death is but another of the attractors shared by the interacting molecules of your body, and your physician's job is to keep your molecules within the basin of the living state. (Unfortunately, the basin shrinks with age, making the task ever more difficult.)

  Because many examples of such nonlinear systems have been studied both experimentally and theoretically [27, 29], there is little doubt about the scientific credibility of this means for downward causation. Building on a seminal suggestion of Alan Turing [31], biologists Stuart Kauffman [19] and Brian Goodwin [14], among others, have presented detailed discussions of ways that WDC can influence the development and behavior of living organisms.
- *Medium downward causation* (MDC). Accepting WDC, proponents of MDC go further in supposing that higher-level dynamics (e. g., the emergence of a higher-level structure) can modify the local features of an organism's lower-level phase space through the downward actions of formal causes. In the modern biology, MDC is a key aspect of evolutionary theory, and in neuroscience, the phenomenon of learning is an example of MDC, in which higher-level experiences (or training) of an organism alter the ways that neurons interact, changing its behavioral spectrum.

5.6.8 Open Systems

In contrast with the conservative formulations of classical physics, biological organisms are open systems, requiring a steady input of energy and matter (sunlight or food) to maintain their metabolic activities. A familiar example of an open system is provided by the flame of a candle – the heat of the flame releases vaporized wax that provides the energy to keep the flame hot.

From the size and composition of the flame and the candle, it is possible to compute the (downward) propagation velocity of the flame (v) whereby establishing a rule for where the flame will be located at a particular time [27].

Corresponding to

$$M_1 \to M_2$$

in Fig. 5.1, such a rule is the following. If the flame is at position x_1 at time t_1, then it will be at position

$$x_2 = x_1 + v(t_2 - t_1)$$

at time $t_2 > t_1$. Because the flame is an open system, it follows that a corresponding relation

$$P_1 \to P_2$$

cannot be written – not even "in principle" – for the physical substrate. Why not? Because the atoms comprising the physical substrate are *continually changing* [5]. The flame's heated molecules of air and wax vapor at time t_2 are entirely different from those at time t_1. Thus, knowledge of the detailed positions and speeds of the molecules present in the flame at time t_1 tells us nothing about those at time t_2. What remains constant is the flame itself – a higher-level process.

Although it might be asserted that "in principle" one could compute the dynamics of all the matter and all the radiation of the universe, this would require an "omniscient computer," which is similar to the Calvinist notion of God. Such speculation tells us nothing about reductionism.

5.6.9 Closed Causal Loops

In his analysis of reductionism, Kim misses the concept of a closed causal loop, asking: "How is it possible for the whole to causally affect its constituent parts on which its very existence and nature depend?" [21]. Causal circularity, he claims, is unacceptable because it violates the following "causal-power actuality principle."

> "For an object, x, to exercise, at time t, the causal/determinative powers it has by virtue of having property P, x must already possess P at t. When x is being caused to acquire P at t, it does not already possess P at t and is not capable of exercising the causal/determinative powers inherent in P."

There are two replies to this assertion, one theoretical and the other empirical.

From a theoretical perspective, Kim errs in supposing that an emergent structure somehow pops into existence at time t, which would indeed be surprising. An emergence entity (or coherent structure), however, begins from an infinitesimal seed (noise) that appears at a lower level of description and develops through a process of exponential growth (instability). Eventually, this growth is limited by nonlinear effects, and a stable entity comes into existence. Think of lighting a candle. Upon being barely lit, a tiny flame grows rapidly before settling down to its natural size.

Similarly, in Kim's notation, both x and P should be viewed as functions of time (t), which may be related by ordinary differential equations as

$$\frac{\mathrm{d}x}{\mathrm{d}t} = F(x, P) \, ,$$
$$\frac{\mathrm{d}P}{\mathrm{d}t} = G(x, P) \, ,$$

where F and G general nonlinear functions of both x and P. (The time scales of F and G can be very different, allowing P to remain approximately constant during the dynamics of x.) The emergent structure is not represented by $x(t)$ and $P(t)$ (which are functions of time and can be infinitesimally small), but by x_0 and P_0 satisfying

$$0 = F(x_0, P_0) \, ,$$
$$0 = G(x_0, P_0) \, .$$

Assuming that x_0 and P_0 are an asymptotically stable solution of this system,

$$x(t) \to x_0 \, ,$$
$$P(t) \to P_0 \, ,$$

as $t \to \infty$ exemplifying the establishment of a dynamic balance between downward and upward causations.

Thus, Kim's causal-power actuality principle is recognized as an artifact of his static analysis of an essentially dynamic situation.

Empirically, there is much evidence for closed causal loops. Going back to James Watt in the eighteenth century, engineers have used negative feedback to "govern" the speed of engines. Since the 1920s, negative feedback loops are invariably used to stabilize the performance of electronic amplifiers, making long-distance telephone communications possible, and they play key roles in Wiener's science of cybernetics [34]. Such closed causal loops can be represented as

$$\begin{tikzcd} & \textbf{Emergent entity} \arrow[d, shift right=4] \\ & \textbf{Underlying phase space} \arrow[u, shift right=4] \end{tikzcd}$$

a positive feedback diagram. Over two decades ago, biochemists Manfred Eigen and Peter Schuster suggested that closed causal loops around at least three levels of dynamic description were necessary for the emergence of living organisms from the oily foam of the Hadean oceans [8].

In engineering applications of closed causal loops, a signal from the output is brought back to the input, as shown in Fig. 5.2a. Here **A** causes **B**, which in turn causes **A**, confounding the concepts of cause and effect. Occasionally, the net gain around the loop exceeds unity, leading to oscillations (called "singing"), for which cause and effect are indistinguishable. Oscillations are

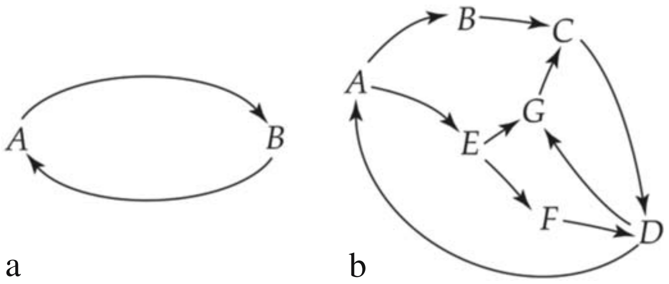

Fig. 5.2. Feedback diagrams in which the arrows indicate the actions of causality. (a) A simple loop. (b) A complex network

unwanted emergent structures in amplifiers, but for systems that are intended to oscillate, positive feedback is an essential element of the design.

Journals of nonlinear science offer many examples of positive feedback and the subsequent emergence of coherent structures [27]. In the physical sciences, structures emergent from positive feedback loops include tornadoes, tsunamis, optical solitons, and Jupiter's Great Red Spot, among many others. Biological examples include the nerve impulse, cellular reproduction, flocks of birds and schools of fishes, and the development of new species, in addition to the emergence of life itself. In the social sciences, there are lynch mobs, natural languages, and the founding of a new town or city [29]. In hierarchical systems, downward causation (WDC, MDC, or both) leads to additional opportunities for more intricate closed causal loops (or networks), as is suggested in Fig. 5.2b. Here the network comprises the following closed loops of causation: **ABCD**, **CDG**, **AEFD**, and **AEGCD**, where the letters correspond to coherent entities at various levels of the biological and cognitive hierarchies. In the context of modern nonlinear science, each such diagram would correspond to the presence of an attractor in the phase space describing the system dynamics, and it could lead to the emergence of a new coherent entity of theoretically unbounded complexity.

5.7 Concluding Comments

As we have seen, there are several reasons for questioning reductionism in the context of classical (nonquantum) dynamics. First, although the reductive program asserts that all higher-level dynamics can "in principle" be causally explained in terms of physics and chemistry, reductionism does not imply constructionism. This is because there is an immense number of possible emergent entities at each level of both the biological and the cognitive hierarchies, so what actually occurs depends largely on happenstance (Poincaré's "fortuitous phenomena") that is consistent with but not constrained by the laws of physics and chemistry.

Second, reductionism does not explain how the various types of Aristotelian causality (material, formal, efficient, and final) are to be sorted out. Under nonlinear dynamics, even the threads of efficient cause become interwoven, and downward action of formal causes makes lower-level dynamics depend on higher-level phenomena, at variance with reductive assumptions.

Third, from an operational perspective, the nature of time differs at higher and lower levels – the "arrow of time" being bidirectional under energy conservation and unidirectional under the energy-consuming dynamics of biology. This is problematic for biological reductionism because a system with unidirectional time is asked to be described in terms of bidirectional time.

Fourth, living creatures are open systems, regularly replacing their atomic and molecular constituents. Thus exact knowledge of the speeds and positions of these constituents at one time cannot be used for making higher-level predictions at later times.

In biological and cognitive systems, finally, myriad closed causal loops and networks with positive feedback obscure the relationships between cause and effect, leading both to the emergence of new dynamic entities with unanticipated properties and to chaotic interactions among them.

In describing a human being from the perspective of nonlinear science, the possibility of causal interactions among the various levels of both the cognitive and biological hierarchies must be included in the overall theoretical formulation. At lower levels, this is evident because the physiological condition of a neuron clearly affects the manner in which it relates incoming and outgoing streams of information, but higher cognitive levels also have causal biological effects. Cultural imperatives to ingest a psychoactive substance, for example, can alter the dynamics of membrane proteins, leading to mental changes that influence bodily health with subsequent psychological effects in a wending path of branching causes and effects that staggers the imagination and daunts analysis. Thus one can easily imagine corresponding feedback diagrams that are far more intricate than in Fig. 5.2b.

The types of phenomena that could emerge from such intricate networks of closed causal loops – spanning several levels of both the biological and cognitive hierarchies – are yet only dimly imagined, but some theoretical work is underway. Building on the seminal work of Eigen and Schuster on the emergence of life [8], several scientists are attempting to formulate relationships among levels of a nonlinear dynamic hierarchy in a manner that is suitable for mathematical analysis [4, 11, 23, 32]. This is not a trivial matter because the time and space scales for models of living creatures differ by many orders of magnitude as one goes from the biochemical levels to the whole organism, creating a challenge for the numerical modeler. Are there ways to evade such computational constraints? Might hierarchically organized functions be defined on nested sets of points, with different rules of averaging at various stages of the computations? Is it possible to resolve key issues without resorting to mind-numbing numerical computations?

In conclusion, consider two questions.

- Can one comprehend the nature of life without lapsing into nineteenth-century (Bergsonian) vitalism?
- Is it possible to provide a credible explanation of human consciousness without resorting to Cartesian dualism?

In response to the first question, few biologists now doubt that the phenomena of life – including both its emergence from the chemical scum of the Hadean seas and its subsequent evolution – will eventually be understood as a complex process comprising many closed causal loops and networks of positive feedback that thread through several levels of nonlinear dynamics.

Although the answer to the second question is less clear, I have these comments. Accepting physicalism and rejecting substance dualism (as I do) does not require me to accept reductionsim; indeed, the burden of proof lies with the reductionist. In other words, reductionism is not a conclusion of science but a belief of many scientists, leaving the door open to a property dualism that is rooted in physicalism. As well as substance dualism, this property dualism may allow the phenomena of human consciousness to emerge from interactions among myriad positive feedback networks that engage many levels of both the biological and the cognitive hierarchy.

Understanding the nonlinear dynamics of such intricate emergent structures is a central task for twenty-first century science.

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