PCID 2.3.7, October 2003

THOUGHTS ON THINKING MATTER

James Barham

1. Introduction

The word *design* is commonly used to refer to either a process of conscious reflection and planning, or the product of this process. Either way, it is essentially connected with *thinking.* In the process sense, design connotes the particular end that a thinking agent has in mind. For instance, my design may be to build a better mousetrap. In this sense, design is both intentional (directed toward having more dead mice) and normative (more dead mice is good). In the product sense, design refers to a particular organization imposed on matter by the agent as the means to an end. In this example, the new arrangement I come up with is the means embodied in matter for the fulfillment of the end of more dead mice. In this sense, design is teleological (more dead mice is its goal).

Like a number of problems in biology, design presents us with a chicken-and-egg sort of circularity. Mousetraps are designed by minds instantiated in brains, but brains themselves seem to be a lot like mousetraps. That is to say, to many, neurons seem to be arranged for the sake of thinking in much the same way that springs and levers in mousetraps are arranged for the sake of dead mice. But if that is so, then who or what designed brains? Perhaps human brains were designed by other minds somewhere else---say, in another galaxy or on another plane of being (this is the *Intelligent Design* position). But if these other minds are supposed to be instantiated in matter, then we have the same problem all over again. If not, then we are left with disembodied minds---which are even more mysterious than the embodied sort. To avoid both horns of this dilemma, a completely different approach is required.

What might this different sort of explanation be? The most popular candidate at present is a loose collection of mutually supporting propositions that I shall call the *Mechanistic Consensus*. The Mechanistic Consensus holds, roughly, that (1) the known laws of physics and chemistry, together with special disciplines like molecular biology, fully explain how living things work; (2) the theory of natural selection explains how these laws have come to cooperate with each other to produce the *appearance* of design in living things; and (3) the theory of computation explains how brains give rise to thinking minds, which may be embodied indifferently in either carbon or silicon. According to the Mechanistic Consensus, then, *life is just chemistry* and *thinking is just computation.*

In this paper, I will try to show that the Mechanistic Consensus is not the only alternative to Intelligent Design. There is also the possibility that certain forms of matter may be *intrinsically* endowed with mind-like properties, that these properties are irreducible to mechanistic interactions, but that they may nonetheless be subject to investigation by the methods of empirical science.

This proposal is nothing new. Recall the following passage from Locke's *Essay* (IV.iii.6):

> We have the *Ideas* of *Matter* and *Thinking,* but possibly shall never be able to know, whether any mere material Being thinks, or no; it being impossible for us, by the contemplation of our own *Ideas*, without revelation, to discover, whether Omnipotency has not given to some Systems of Matter fitly disposed, a power to perceive and think, or else joined and fixed to Matter so disposed, a thinking immaterial Substance: It being, in respect of our Notions, not much more remote from our Comprehension to conceive, that GOD can, if he pleases, superadd to Matter a Faculty of Thinking, than that he should superadd to it another Substance, with a Faculty of Thinking; . . . (Locke, 1975, pp. 540--541)

Admittedly, Locke does not believe that thinking matter could ever be understood as a purely natural phenomenon. On the contrary, he says that the power to perceive and to think could only have been "superadded" to inert matter by God. Therefore, in today's terms, he would have to be accounted an adherent of Intelligent Design.[1] However, he *is* saying that the idea of thinking matter is not absurd---that nothing in the concept of matter contradicts anything in the concept of thinking. Of course, it is one thing to say that by being "fitly disposed" matter might conceivably acquire the intrinsic power to perceive and to think. It is something else to say in what such a fit disposition might consist, and how it might actually come to exist in nature. Nevertheless, if Locke was right and thinking matter is no oxymoron, then the idea cannot be dismissed out of hand. It remains a possibility to be evaluated in the light of empirical science.

No doubt, most readers will assume that empirical science passed a negative judgment on this idea long ago. They will feel that today thinking matter is at best a bare possibility, not a live one. Certainly, the proposition that a certain kind of matter has an intrinsic power of thought flouts the spirit of the Mechanistic Consensus. However, I shall argue below that the Mechanistic Consensus is mistaken in each of its main theses: (1) present-day physics and chemistry do not provide the conceptual resources for a complete understanding of how living things work; (2) natural selection does not provide an adequate ground for naturalizing the normative teleology in living things, which is no mere appearance, but rather objective reality; and (3) thinking is not just a matter of computation, nor does the normative character of thought have anything to do with brains *per se*. The upshot of these negative arguments will be that *living matter is special*. Finally, I will conclude on a more positive note by briefly reviewing some ways in which we might begin to understand this specialness scientifically.

2. The Mechanist's Dilemma

Everyone will agree, I think, that both the behavior of cells and their internal organization give the appearance of purposiveness.[2] That most or all living processes constitute *functions*; that biological functions operate according to a means-ends logic; that functional ends constitute norms whereby the means chosen may be judged good or bad, right or wrong, successful or unsuccessful; that organisms are capable of choosing means appropriate to their ends, at least some of the time; and that therefore such intelligent choices may be said to constitute actions taken for reasons, as opposed to events due to causes---all of these are natural descriptions of observable biological phenomena. To be sure, such pretheoretical, everyday locutions are usually held to be without scientific value, like talk of the rising and setting of the sun. However, reductionism presupposes the existence of a theoretical framework from which all traces of teleology and normativity have been eliminated and into which "folk-psychological" terms can be translated without remainder. But does the Mechanistic Consensus in fact provide us with such a framework?

Open any cell biology textbook to any page, and what will you find? Talk of *regulation, control, signals, receptors, messengers, codes, transcription, translation, editing, proofreading,* and many other, similar terms. It is true that this technical vocabulary is an indispensable aid in describing many previously undreamed-of empirical phenomena. In the manner of any science, molecular biology has greatly extended the scope and precision of our knowledge, and the terminology it has developed is an integral part of that accomplishment. But the fact remains that these concepts are no less normative than those of everyday speech. Adherents of the Mechanistic Consensus are untroubled by this inconsistency, because they insist it is only a matter of convenience. A term like "second messenger," they say, is a metaphor that, while not strictly necessary, is useful in order to avoid intolerably verbose descriptions of the mechanistic interactions that underlie the appearances. Such a *façon de parler* is a promissory note redeemable in the hard currency of physics and chemistry. But like any IOU, this promise issued by molecular biology is only as sound as the other sciences backing it up. If they cannot make it good, then the note is worthless. Therefore, it behooves us to take a closer look at the conceptual solvency of the Mechanistic Consensus.

First of all, we are told that living things are made of ordinary matter and nothing but ordinary matter. And it is true that biological molecules are composed mostly of a handful of elements (CHNOPS), along with traces of some others, all long familiar to chemists. Certainly, there are no unknown elements in living things that are not present in the periodic table. Second, we are assured that the interactions between these elements are basically the same *in vivo* and *in vitro,* as described by present-day physics and chemistry. This is a more doubtful claim, to which I shall return later, but for now, let us grant this, too. Even so, there remains a fundamental difficulty.

This is that, while all the individual reactions in the cell may be described in ordinary physical terms as tending towards an energy minimum, the same cannot be said of the way in which the reactions are organized. When a signal molecule (say, a hormone) interacts with its receptor (a protein), what happens may be more or less understood in terms of biochemistry. But biochemistry has no conceptual resources with which to explain the meaning and the purpose of this reaction---the very things that constitute the reaction *as* a signal, and not just a meaningless jostling of matter. What makes the living cell profoundly different from ordinary inorganic matter is the way in which each reaction is coordinated with all the others for the sake of the whole. There is no doubt that this coordination itself transcends the explanatory resources of biochemistry, because it operates according to functional logic, not just physical law (Jonker et al., 2002; Pattee, 1982; Rosen, 1991, 2000).

From a purely physical point of view---at least so far as our present state of knowledge is concerned---there is no reason why a reaction that is good for the organism should occur rather than one that is bad for it. Normativity simply has no place in physics or chemistry as currently understood. And yet it is at the very heart of life. Every reaction in the cell is more than just a reaction, it is a functional action. Such an action constitutes a *choice* among states that are energetically equivalent so far as the ordinary laws of physics are concerned. Such preferred states are achieved, not by minimizing energy, but by doing *work*---that is, by directing internally stored energy here or there according to *needs* that are normative for the cell. Just as the laws of physics permit me to direct my automobile left or right at an intersection, so too they permit a cell to travel up or down a chemical gradient (Albrecht-Buehler, 1990, 2000; Alt, 1994; Lauffenburger & Horwitz, 1996). There is no use seeking the explanation of such decisions in the physical forces impinging on me or the cell. It is not physics (at least, not any presently understood physics) that explains such purposive actions. Rather, it is the functional logic of the situation. *This* is done so that *that* may happen. A is preferred; B is necessary for A; therefore, B is chosen. I want to mail a letter; to do this I need to get stamps at the post office; therefore, I turn left. The cell wants to go on living; to do this it needs nourishment; therefore, it moves up the gradient. All functional action conforms to this pattern.

Now, during the past fifty years or so we have developed a highly sophisticated theoretical framework to explain how such coordinated, goal-directed action works---namely, the theory of feedback and cybernetic control. This theoretical understanding has made possible the construction of complex, self-regulating mechanical systems that operate according to a functional logic similar to that in living things, to fulfill a wide variety of human purposes. There is no doubt that this body of theory provides a great deal of insight into the internal operation of biological systems, as well. But there still remains a glaring problem. In the case of the machine, *we* decide what counts as its functional state and *we* arrange its parts accordingly. Who or what does these things in the case of the cell?

It is often assumed that invoking the concept of *information* will somehow make this problem go away. It is undoubtedly true that all living things utilize information in *some* sense (Loewenstein, 1999). It is equally true that functional correlations between different species of molecules constitute languages or codes in *some* sense (Barbieri, 2002; Gabius, 2000; Strahl & Allis, 2000). Unfortunately, however, these notions do little more than label the problem; they do not solve it. The reason is that information has an irreducibly semantic dimension. Without meaning, there is no information; there are just spatial or temporal patterns. For a pattern to constitute information, we must posit a cognitive agent for which the pattern is meaningful. What is information in the semantic sense? One plausible answer is that *information is a correlation between events and functional actions without thermodynamic coupling.* Such a correlation can be used by a nonlinear oscillator as a guide to functional action. In this way, the meaning of information may be interpreted as a sign of the presence of favorable conditions for functional action. That is, information is not an ordinary cause, because nonlinear oscillators are not tightly coupled to their surrounds. Rather, information is a trigger that acts as a sign that says: Act now, and you will succeed (Barham, 1996). But how such a correlation is possible is the very thing we have been trying to fathom. Information theory simply assumes intelligent agents at either end of the communication channel; it makes no pretense of explaining how physical patterns can acquire meaning in the first place. Therefore, the concept of information is simply another way of referring to the problem we are discussing. In its present theoretical articulation, it contributes little or nothing to a solution.

If the functional logic of the cell is irreducible to physical law as we currently understand it, then there would appear to be only two ways for the naturalist to go. Either (1) the existence of functional logic in the cell is at bottom a matter of *chance*; or else (2) there is some unknown qualitative difference about the material constitution of cells that gives them an intrinsic functional integrity. The first option is appealing to the mechanistic biologist, but it is very hard for the physicist to swallow because of the fantastic improbability of living things from a statistical-mechanical point of view, as has often been pointed out (Eden 1967; Elsasser 1998; Lecomte du Noüy, 1948; Schoffeniels 1976; Yockey 1992). The second option has attracted a number of physicists who have thought seriously about life (Bohr, 1987; Denbigh, 1975; Elsasser, 1998; Laughlin et al., 2000; Polanyi, 1969; Schrödinger, 1992), but is unpalatable to most biologists because to them it smacks of pre-scientific "vitalism."

This, then, is the Mechanist's Dilemma. Is life a statistical miracle? Or is the Mechanistic Consensus defective in some fundamental way? I will examine the first horn of this dilemma in the next section. I will return to the other one in Section 5, below, after a brief detour to look at brains.

3. Normativity and Natural Selection

According to the Mechanistic Consensus, the things that happen in organisms do not really happen for a purpose; it only looks that way. In reality, things just happen. Period. What happens in the organism is no different from what happens in the test tube. Enzymes cleave or bond their substrates according to the well-known laws of physics and chemistry. A catalyst is a catalyst is a catalyst. How, then, do mechanists explain the appearance of purposiveness in living things?

They say that some of the things that happen in an organism sometimes have by chance the consequence that they enhance the organism's *fitness*, meaning that the probability of the organism's surviving to reproduce within a given set of environmental conditions is increased on account of the physical or chemical event in question. When this happens, the propensity for that event to occur will be transmitted to the next generation. Then, the event in question will tend to recur and to have the same consequence in the offspring, so long as the same environmental conditions persist. And likewise in the offspring's offspring. In this way, the representation of the original event in the population at large will gradually increase. At the limit, an event that occurred in a single organism will occur in all the members of a population. In that case, it will appear as though these organisms had been designed for their environment with respect to the event in question. But in reality all that will have happened is that the process of natural selection will have locked into place an event that originally occurred by chance insofar as the fit with the environment is concerned.

It is assumed that this explanatory scheme gets rid of all the troublesome teleology in biology. But it does not. Natural selection provides only the appearance of reduction, not the reality, as may be seen from a number of considerations. To begin with, we may note that the notions of *survival* and *reproduction* undergird the entire Darwinian schema, and are not themselves explained by it. But these concepts already remove us from the *terra firma* of physical interactions and land us right back in the teleological soup. Atoms, molecules, and more complex assemblies of inorganic matter just seek their energy minimum. To say that a chemical compound "survives" or that a crystal "reproduces" itself is to employ metaphors that obscure the point at issue. The very thing we are trying to explain is how it is possible for an organism to direct energy in a way that promotes its self-preservation, and not in other energetically equivalent ways. Thus, the notions of survival and reproduction already contain the normative feature of striving to achieve particular preferred states. They are far from the unproblematic mechanistic concepts that a successful reduction would require. Rather, they demarcate the boundary between the living and the nonliving, and so constitute the very heart of the problem of teleology.

Another problem is the way that selection theory invokes the notion of chance. In order for Darwinian reduction to go through, we must assume that an organism's parts are essentially independent variables, each of which varies without correlation to the other parts or to the whole organism's needs. But if organisms really were made of inert, functionally uncorrelated parts, then evolution would be impossible due to combinatorial explosion. If organisms were literally machines, they would be miraculous. There has simply not been enough time since the Big Bang for even a single protein molecule to be created in this way with any reasonable probability, much less an entire cell. Much less the whole inconceivably complex, functionally integrated organic world we see around us. On this point, the Intelligent Design critique of Darwinism is perfectly sound. If organisms really were machines made of inert parts bearing no intrinsic relation to function, then we would indeed have to assume that they were designed by a humanlike intelligence, because that is the only conceivable way for functionally integrated wholes made of such parts to come into existence.

However, this does not mean that we are forced to accept the Intelligent Design conclusion. We may just as well reject the premise, instead. In that case, we may say that the "design inference" (Dembski, 1998) constitutes a *reductio ad absurdum* of the proposition that organisms are machines. If we drop this premise, then we are free to view organisms as active and fully integrated systems, in which a change in one part leads to appropriate changes cascading throughout the system in accordance with functional logic. In this case, evolution begins to make sense from a physical point of view. *But now Darwinism has forfeited all of its reductive power!* We have simply *assumed* the functional organization of the cell, which is the very thing we claimed to be able to explain by means of the theory of natural selection.

Darwinians often complain that such criticisms are based on a misunderstanding. It is not chance, they say, that bears the explanatory weight in their theory, it is the selection principle. Natural selection is said to act as a *ratchet*, locking into place the functional gains that are made, so that each new trait can be viewed as a small incremental step with an acceptable probability. But what Darwinians forget is that the way a ratchet increases probabilities and imposes directionality is *through its own structure*. In the present context, the structure of the ratchet is simply the functional organization of life. Darwinians are only entitled to claim that the explanatory burden of their theory lies on the selection "ratchet," thus avoiding the combinatorial explosion problem, provided that they also acknowledge that the structure of this ratchet consists precisely in the intrinsic functional correlations among the parts of the organism. But now they have merely assumed the very functional organization that they claimed to be able to explain, thus sneaking teleology in by the back door.

Finally, it is often claimed (e.g., Depew & Weber, 1998) that the normativity of biological functions can be fully naturalized in terms of Wright's (1998) analysis, in which a function is a part of a system that exists because of the role that it plays within the system. In the case of biological functions, normative functions are traits that have been selected. That is, if a given trait happens to do X, and X happens to cause the trait to be favored in the selection process, then X becomes the *proper function* (Millikan, 1998) of that trait as a result of having been selected. But this analysis reduces the problem of naturalizing normativity to a matter of agreeing on a terminological convention; it has nothing to do with scientific explanation in the usual sense.

Of course, science often looks to history to explain how the present state of a system came into being, but the present causal powers of a system must nevertheless be explicable in terms of the system's present state. After all, "history" is just a convenient shorthand way of referring to the whole sequence of dynamical states of a given system, the past transformations of which have led to the system's present state. But this sequence in itself does not explain the present properties and causal powers of the system; rather, these are explained by the present physical state of the system, which is the only thing that is actual. We must not confuse the *present effects* of history with history as such. Living systems are physical systems, and there is no reason to believe them exempt from this fundamental metaphysical principle. Therefore, we must conclude that it is something in the present state of a biological function that accounts for its normativity, not its selection history *per se*.[3]

In summary, the massive coherence and coordination of the parts of biological systems---all intricately correlated so as to support those systems in existence as organized wholes---must arise either by chance or by some ordering principle conforming to functional logic. Elementary considerations of statistical mechanics and probability theory suffice to exclude the chance hypothesis.[4] Therefore, there must exist an ordering principle. Such a principle is logically prior to selection, since novel biological forms must already exist before they can be "selected." Indeed, all viable novel forms are always already entrained into a fully integrated functional system *before* selection occurs. Therefore, variations in living form are the cause of differential reproduction, not the effect. This means that the theory of natural selection tacitly presupposes the functional integrity and adaptability of organisms. Which is another way of saying that Darwinism begs the question of teleology.

4. Against Formal Emergence

In the last two sections we have seen that, contrary to received opinion, neither molecular biology nor the theory of natural selection succeeds in reducing the teleological character of life to mechanism, because they both tacitly presuppose it. I promised that after the critical work was completed, I would turn to a more positive examination of thinking matter in the light of contemporary science. Before doing so, however, I would like to try to dispel one other widespread misconception. That is the idea that brains, conceived of as abstract computational devices, somehow contain the secret of normativity. We ordinarily assume that thinking---in the sense of conscious awareness, rational reflection, and foresight---exists only in human beings, or, at best, in a few of the higher animals with large brains. Of course, I do not wish to dispute the obvious fact that thinking in the usual sense is dependent upon big brains. However, I do wish to question the assumption that brain-based rational thought is essentially different from other living processes with respect to its normative character. I believe that this is a fundamental error that must be corrected before we can hope to get a clear view of the problem of design.

The dominant view of the mind in post-war philosophy and cognitive science has been *functionalism*---the doctrine that rational thought is essentially constituted by a particular abstract pattern or organization, and not by any properties or powers of living matter. This organization is usually explicated, in turn, in terms of the theory of computation. Rational thought just *is* computation. Furthermore, if two computational devices are functionally equivalent, then they are equivalent in all other metaphysically relevant respects, as well. That is to say, if they are organized according to the same abstract pattern, then they will have equivalent properties and powers whether they are embodied in carbon or in silicon. This is because, according to the orthodox view, there is nothing to being a function above and beyond having a particular type of abstract organization.

It is usually assumed that the right kind of organization must include threshold effects, that a certain level of complexity must be crossed before real thinking "takes off" (Chalmers, 1996; Kurzweil, 1999; Pinker, 1997). Let us call this doctrine *formal emergence* (see Barham, 2002b). On this view, brains, be they natural or artificial, occupy a special metaphysical category. As a result, those naturalistically inclined thinkers who countenance talk of *value* at all[5] tend to see it as essentially connected to brains. Brains are the ground of normativity in nature; all else is mindless machinery. I believe that this gets things exactly backwards. The truth is that life is more than just machinery, and there is nothing special about brains, at least from the point of view of normativity.

The notion of formal emergence is a very important ingredient of the Mechanistic Consensus. If life and mind are mechanical, then biological functions must be at bottom just like manmade machines---that is, abstractions that can be "instantiated" in arbitrary matter. Just as a "clock" may indifferently employ water, sand, a pendulum, gears and springs, or cesium atoms to keep time, so too may a "heart" employ smooth muscle tissue or titanium and dacron parts to pump. And so too may a "brain" employ neurons or cathode ray tubes or transistors or microchips to think. In short, functions are essentially software; they have little or nothing to do with hardware. Rational, normative thought, then, emerges out of the complexity of the software run on the "wetware" of the brain, but could just as well run on a suitably sophisticated form of hardware. It is the software---the abstract logical relationships---that constitutes the normative thinking, not the clanking machinery of the brain *per se*. Brains are special only in that they are complex enough to run the right software for producing thought.

Unfortunately, the idea that patterns *per se* can have distinctive causal powers flies in the face of both science and our commonsense experience of the world. In the inorganic world, certainly, it is clear that the organization of matter arises from its physical properties, not the other way around. The crystal lattice in a piece of marble exists on account of the mutual forces exerted by all the atoms constituting the lattice. It is these forces that give the lattice the global properties of rigidity and impenetrability. It is not the case that lining up just anything (say, a tinker toy model) into the pattern of a calcium carbonate crystal will produce these same properties.

The notion of formal emergence rests on a deep confusion at the heart of the Mechanistic Consensus---a fundamental equivocation between functions conceived of as patterns constituted by externally imposed norms, and functions conceived of as real material processes with intrinsic causal powers. Manmade machines have functions only in a Pickwickian sense. They are merely tools that satisfy *our* needs. Their so-called functional organization is simply a pattern that *we* value. They themselves have no needs and value nothing. Cells, in contrast, evidently possess an inherent power of intelligent agency. No simulation *in silico* is ever going to acquire equivalent powers merely by virtue of the faithfulness of its mimicry. So far as causal powers are concerned, protein remains protein and silicon remains silicon, and never the twain shall meet. We could make a robot to weep hot tears and beg for mercy as we reached for the "off" switch. We could perhaps make it *appear* to fear being switched off to any degree of verisimilitude we liked, but we have no reason to believe we could ever make it *really* give a damn one way or the other. Or, better to say, we could not make *it* really give a damn, as opposed to making it appear to *us* that it did. There is simply no good reason to think that such a thing is possible, even in principle. When it comes to causal powers, matter matters. Why should thinking matter differ from any other kind of matter in this regard?

The original function of brains was to allow a vast community of cells---a multicellular organism---to move through space as an integrated whole in a rapid, coordinated, purposive manner. Everything that evolved later was a refinement on that basic theme. And yet individual cells like bacteria and amoebae---which are themselves vast communities of molecules---also have the power of purposive motion through space as integrated wholes. Therefore, the specific form of intelligence associated with brains should be viewed as an adaptation for the multicellular condition of a general form of intelligence which is ubiquitous in individual cells and which underlies all purposive action. Certainly, brains are special in the sense that they have their own particular function---to enable a spatially-extended confederation of cells to move together as one. But they are not special at all insofar as they are purposive and intelligent. In that respect, they are merely endowed with the same power of intelligent adjustment of means to ends that is an essential feature of life as such. Therefore, there is no difference in kind between brain-based thinking and general natural intelligence, merely a difference in degree.[6] Indeed, one might even go so far as to say that the thinking of brains is merely a refinement of the "thinking" that is an essential property of living matter itself.

Now, I do not wish to attach too much importance to words. It does not much matter whether we allow the term "thinking" to be used in this expanded way or restrict it in the usual way to the conscious, language-and-culture-dependent, reflective activity of human brains. What is important is to frame the problem in the right way. The question is, Does it make sense to explain the purposive and adaptive behavior manifest in all life forms (whatever we choose to call it) on the model of machines that have been consciously designed by brains? Or is it not rather arguing in circles to attempt to understand the human power of conscious thinking in terms of artifacts designed by human thought itself (or by a supernatural power conceived of on the model of human thought)? Does it not make more sense to seek to understand the thinking power of brains as a modification of a general power intrinsic to life as such?

I believe we are well advised to explain the more complex and the evolutionarily later in terms of the simpler and the evolutionarily earlier. Therefore, thinking, in some sense of the term, must predate the emergence of brains. As the late Italian theoretical biologist Martino Rizzotti (1996; p. 2) remarked,

> neuronal activity of the emergent faculties of the brain are by no means essential properties of life: they are just particular manifestations of it . . . Understanding life means understanding bacteria, mushrooms, and amoebae, not brains; cells, not neuronal circuitry. If we aim at moving ahead in understanding life, it is much more important to focus on bacteria than on brains.

In a similar vein, Vertosick (2002; p. 4) recently observed that "to be alive, one must think." In other words, the riddle of life and the mystery of mind are ultimately one and the same puzzle, and the solution to this puzzle can only come from the investigation of the physical basis of cell intelligence---that is to say, thinking matter.

5. Material Emergence and the Ground of Normativity in Nature

In the last section, I argued that (1) normativity is an objectively real attribute of living matter; and (2) formal emergence is contrary to everything we know about the relationship between causality and matter. Now, the conjunction of these two propositions may seem like a counsel of despair. How can we ever hope to understand the natural ground of normativity, if not through emergence or a notion similar to it? Certainly, *some* positive scientific account of normativity is necessary, since it will be difficult, if not impossible, to overcome the Mechanistic Consensus by negative arguments alone. For this reason, I now turn to the consideration of some promising, albeit speculative, lines of research that may perhaps throw light on this question.

First, we must view our problem against the backdrop of a general picture of cosmic evolution (Denbigh, 1975; Layzer, 1990). The key concept here is *spontaneous symmetry breaking,* which is the framework within which the origin all novelty and all complex structures and processes in the universe must ultimately be understood (Icke, 1995). To explain this phenomenon, physicists have developed a variety of mathematical tools (above all, the *renormalization group*) for extracting certain *universal* properties shared by systems across length scales by abstracting away from physically irrelevant details (Batterman, 2002; Cao, 1997). Such techniques work extremely well, and seem to reveal a layered world of hierarchical levels, each with its own intrinsic stability and characteristic physical properties (Georgi, 1989). The idea is that over the course of its history the universe has repeatedly produced qualitatively new forms of matter with distinctive causal powers. Anderson (1994) famously encapsulated this insight in the slogan "more is different" (see, also, Cao, 1998; Dresden, 1998; Schweber, 1997). Thirring (1995) expressed the same idea by speaking of the "evolution" of the laws of nature themselves.

It is true that the asymptotic methods used to model these empirical phenomena have often been interpreted as a makeshift---a gimmick to get around our own cognitive limitations. But this epistemic interpretation of physical theory is based on little more than reductionist faith (Laughlin & Pines, 2000; Laughlin et al., 2001). It flies in the face of the general principle that the best explanation for the success of a theory is that it has a purchase on reality. On the other hand, if we take the success of modern field-theoretic methods in physics at face value, then we begin to see the possibility of a new conception of emergence, one that is directly linked to the properties of matter itself in its various guises. As Auyang (1995; p. 83) has put it:

> The world exhibits many levels of scale and complexity that require radically different descriptions. The classical and the quantum are two such levels, and there are many more beyond physics. Ontologically, we can agree that all systems, no matter how large and complicated, are made up of subatomic constituents. However, this does not imply that the theory for the subatomic constituents is applicable to all systems as integral units. Those who assume that it does have neglected the effect of composition and confused the properties of the parts with that of the whole.

I have proposed that we refer to this notion as *material emergence,* in order to distinguish it clearly from the more usual concept of formal emergence (Barham, 2002b).

What reason do we have to believe that cell intelligence constitutes an emergent phenomenon in the material sense? Batterman (2002; p. 135) notes that "In the physics literature one often finds claims to the effect that [emergent] phenomena constitute 'new physics' requiring novel theoretical work---new asymptotic theories---for their understanding." In other words, wherever novel kinds of material systems are to be found, we ought to expect qualitatively distinctive causal powers, and hence "new physics" to describe those powers. This is already true of the behavior of inorganic matter in its various forms---atoms, molecules, plasmas, gases, liquids, and solids of many different kinds. For example, condensed matter (liquids and solids) required the development of many new physical concepts, and remains imperfectly understood to this day. Why should this same principle not apply to life? Given these considerations, it is not surprising that physicists are beginning to articulate the need to tackle the expected new physics characteristic of the living state of matter head-on (Laughlin et al., 2000).

Of course, this understanding of the general principle of material emergence still leaves us with one very pressing question: How can we make scientific sense out of living---and thinking---matter in particular? There are two lines of research that seem to me to bear directly on this question. The first of these is nonlinear dynamics (Auyang, 1998; Bar-Yam, 1997; Walleczek, 2000a; Yates, 1994). Nonlinear dynamical systems are interesting in this context because their behavior possesses a number of intrinsic properties that seem to be of potential significance for biology. One of these is *robustness*, meaning that the system will spontaneously damp perturbations to its dynamical regime, within limits. Such robust dynamical equilibria may be modeled mathematically as *basins of attraction* (or, simply, *attractors*). Another important property of nonlinear dynamical systems is *metastability*, which means that, within the abstract landscape of possible dynamical regimes available to the system, other attractors exist in the vicinity of the original one. If a metastable system is pushed past the boundaries of its original attractor, it will not necessarily cease its dynamical activity altogether. Instead, it may be pulled onto a new attractor. Such a shift to a somewhat different dynamical regime is referred to as a *bifurcation event.* This phenomenon is of the highest interest for understanding the *directed* or *selective switching* between different dynamical regimes in metabolism and other forms of short-term, or ontogenetic, intelligent behavior in cells (Barkai & Leibler, 1997; Carlson & Doyle, 2002; Jackson, 1993; Jain & Krishna, 2001; Jeong et al., 2000; Mikulecky, 1995, 1996; Petty, 2000; Petty & Kindzelskii, 2001; Savageau, 1996; Yi et al., 2000; Walleczek, 2000b).

Ravasz et al. (2002; p. 1555) point out that "The organization of metabolic networks is likely to combine a capacity for rapid flux reorganization with a dynamic integration with all other cellular function." Nonlinear dynamics gives us a way of conceptualizing and modeling this cascading functional reorganization of relationships among the components of living systems. By showing how new functional states may be found through the operation of physical principles, it may eventually serve as the basis for a genuine understanding of long-term, or phylogenetic, shifts in molecular structures and dynamical regimes---i.e., evolution---as well (Flyvbjerg et al., 1995; Fontana & Buss, 1996; Gordon, 1999; Kauffman, 1993; Stadler, 1995; Webster & Goodwin, 1996; Zhou et al., 2002).

Another interesting property intrinsic to nonlinear dynamical systems is the lack of proportionality between causes and effects in their interactions with the wider world around them. This *disproportionate response* to events impinging upon them from their surroundings is a hallmark of all living things. If organisms are conceived of, not as machines made up of rigidly connected parts, but rather as a dense network of loosely coupled, nonlinear oscillators, each sensitive to a range of specific low-energy inputs from its surround, then the concept of information begins to take on an entirely new shape. On this "homeodyamic" view of the organism (Yates, 1994), information is anything that acts as a *trigger* for the action of such an oscillator (Barham, 1996). The role of such a trigger in the functional action of an organism is to coordinate the timing of actions in such a way that they become correlated with favorable environmental conditions, where "favorable" means tending to support the continued homeodynamic stability of the oscillator. On this view, then, the *meaning* of information consists in the *prediction of the success* of functional action, where "success" likewise means the continued homeodynamic stability of the oscillator. This dynamical interpretation of information begins to give us for the first time a concrete physical picture of how intelligent functional action is possible.

Most, if not all, of the authors of the studies cited above would probably contend that they are working squarely within the Mechanistic Consensus. So, why do I interpret their work as contributing to an eventual replacement of that worldview? In part, because nonlinear dynamics cannot be the whole story. After all, inorganic dynamical systems like hurricanes and candle flames are not alive. They do not utilize information in the dynamical sense outlined above, nor do they draw on internal energy stores to do work against local thermodynamic gradients to preserve themselves in existence---all of which are hallmarks of living things. Rather, they are tightly coupled thermodynamically to their surrounds, and are merely minimizing energy under a given set of constraints. Furthermore, dynamical networks with many of the properties discussed above can be constructed out of inorganic materials, as in so-called "neural networks." And yet, when all is said and done, a neural network is just fulfilling *our* functions, not its own. It has no internal tendency to prefer one energetically equivalent configuration over another. We are the ones who choose what is to count as a "better" solution to a given problem. Once all the constraints are set---by us---everything else is just minimizing energy.

With nonlinear dynamics, we still have not penetrated to the heart of the mystery, where the leap from passive energy minimization to the active directing of energy in accordance with preferred goal states occurs. What is still lacking is some understanding of how it is possible for dynamical networks to *strive* to maintain themselves in existence. To fill in this missing piece of the puzzle, we must go beyond nonlinear dynamics, which appears to be necessary but not sufficient for understanding thinking matter.

The other promising line of research mentioned above lies in the investigation of the cell as a condensed-matter system. There are several different approaches here that will eventually need to be integrated together. One is the work on the global properties of the protein--phosphate--ordered water gel that constitutes the main phase of the cytoplasm in all living cells

(Ho et al., 1996; Pollack, 2001; Watterson, 1991a, 1991b, 1997, 2001). Another is the work stressing the direct link between the physical structure of the cell components and the coordination of cellular functioning (Clegg, 2001; Hochachka, 1999; Kirschner et al., 2000; Surrey et al., 2001; Whitesides & Grzybowski, 2002). A third is the work on the intrinsic dynamical properties of proteins arising from their energy degeneracy and manifold, competing self-interactions ("frustration") (Frauenfelder & Wolynes, 1994; Frauenfelder et al., 1991, 1999). Finally, there is the highly suggestive, if speculative, work on adapting the formalism of quantum field theory for use in describing the directed transfer of energy along macromolecular chains via coherent resonances within a hypothetical electric dipole field (Fröhlich & Hyland, 1995; Ho, 1997, 1998; Li, 1992; Vitiello, 2001; Wu, 1994). All of these approaches share the assumption that there is more going on in the coordination of functional action *in vivo* than can be explained by mechanistic interactions observed to date *in vitro* or even *in silico* (Srere, 1994, 2000). It is becoming clear that new, non-destructive experimental techniques for probing the real-time dynamics of macromolecular interactions *in vivo* are needed if we are ever to achieve a genuine theoretical biology (Laughlin et al., 2000).

How can such research programs help us to understand normativity as a natural phenomenon? By showing how life is "an expression of the self-constraining nature of matter" (Moreno Bergareche & Ruiz-Mirazo, 1999, p. 60). Ultimately, this means showing how living systems function as integrated wholes, using information in the dynamical sense, and doing work, to maintain themselves in existence. It means showing how a mere physical system can acquire the capacity for striving and preferring and caring, how it can become a *self* existing *pour soi* (Jonas, 1982). And it means showing how all of this occurs through a process of material emergence that is irreducible to mechanistic causation.

It is of course impossible to say exactly how this happens in advance of the scientific breakthrough that will spell it all out in detail. Whether any of the specific lines of research alluded to above is on the path that will ultimately be proven correct remains to be seen. But what is most important is that there are already ideas on the table that seem to be moving us in the right direction. Today, thinking matter is no longer scientifically unthinkable.[7]

6. Conclusion

Throughout this paper, I have used "thinking matter" as a kind of shorthand for the nexus of problems surrounding the phenomenon of natural normativity and intelligence, including *acting* for a *reason* (as opposed to obeying a law of nature), *striving* to reach a goal (*preferring* some states of affairs to others), and *knowing* how to adjust one's actions in the light of circumstances in order to *succeed*. These are all aspects of one and the same fundamental problem---the problem of biological function, understood teleologically and normatively. Natural intelligence in this sense cannot be explained in terms of mechanistic interactions for the simple reason that its essence consists in doing *work* in order to regulate, coordinate, and organize those interactions for the sake of a *preferred state* that cannot itself be explained as merely seeking an energy minimum.

This working and this preferring constitute a striving or caring that is the real ground of normativity in nature. This natural normativity is intrinsic to life, but extrinsic to machines. For this reason, it is a mistake to suppose that invoking the machine metaphor reduces the normativity manifest in life to mechanistic interactions without remainder. No one can deny that, as a methodology, the machine metaphor has been extremely fruitful---even if there are many signs that we are now bumping up against the limits of its usefulness in biology. But however that may be, as a metaphysics, mechanism is quite simply incoherent. The idea that a machine could occur naturally at all, much less that it might have its own intrinsic purposes, is simply an article of faith for which there is not one shred of evidence. And natural selection is of no avail here, either, because it merely presupposes the functional organization it purports to explain.

Looked at aright, the concept of thinking matter is just plain common sense. After all, it just *obvious* that living matter is fundamentally different from inanimate matter, and that one of the hallmarks of this difference is its *intelligence*, in the sense of its ability to adjust means to ends? One has only to watch a cell moving purposively under a microscope to see that this must be so (Albrecht-Buehler, 2000). For that matter, one has only to cut one's own finger and watch what happens over the next few minutes, hours, and days. If this homely and venerable truth has been lost sight of in recent times, it is undoubtedly because the mysteriousness of thinking matter has made it ripe for exploitation by critics of a mystical or religious bent. I think it is mainly for this reason that naturalists have seized upon every advance in biology since Friedrich Wöhler synthesized urea in 1828 to proclaim that "organic macromolecules do not differ in principle from other molecules" (Mayr, 1982; p. 54). But this claim is only compelling against the backdrop of a reductionist metaphysics. Against the backdrop of a metaphysics of material emergence, it is a *non sequitur*. Why indeed should we not believe that organic macromolecules are very different in principle from small molecules, when even liquids are very different from gases, and solid matter is very different from both? If more really is different, then why should those behemoths, proteins, not have special causal powers that small molecules do not have? And, besides, why should biologists feel that they must be *plus mécanistes que les physiciens*?

Still, it is imperative to emphasize, as well, that an attack on the Mechanistic Consensus does not constitute an attack on science, nor does it dispute any operationally verifiable scientific results. As Unger (2002; p. 10) has recently reminded us, what we have been discussing is "a particular *philosophical approach to* science, rather than something science itself actually delivers" (original emphasis). Accordingly, I have tried to take a more positive approach, as well, and have surveyed some recent areas of scientific research that appear to hold some promise of allowing us to eventually understand the phenomenon of thinking matter within a dynamical and emergentist cosmic evolutionary framework.

Whether any of these ideas will bear fruit, of course, only time will tell. But one thing is sure. It is not necessary to choose between mechanistic reductionism and Intelligent Design. Thinking matter, in the sense of natural intelligence, is a perfectly coherent concept, as Locke noted long ago. I have tried to show that it is also a philosophically and scientifically attractive one.

Acknowledgment

I would like to express my heartfelt thanks to all my friends---Darwinian, Christian, and "left-Aristotelian"---and to absolve them all of responsibility. Philosophy makes strange bedfellows.

Notes

1. For Locke's own views, as well as their historical context, see Anstey (2001), McCann (1994), Wilson (1979), and Yolton (1983).

2. It is sometimes held (e.g., Searle, 1992) that purposive action must be essentially linked to conscious experience or feeling. If that were the case, then a realistic attitude towards it would imply that cells too are conscious. However, while it is *conceivable* that natural teleology and consciousness are co-extensive in nature, I see no reason to assume that they are. There is nothing in the idea of coherent, coordinated, goal-directed action that logically implies subjective awareness, so far as I can see. Therefore, I prefer for now simply to bracket the question of whether "there is anything that it is like" to subjectively experience purposive action.

3. For a fuller presentation of this argument, see Barham (2002b).

4. Chance may still play a more modest role, of course. The role that chance plays in evolution is analogous to trial-and-error search in individual organisms. All learning, whether ontogenetic or phylogenetic, involves groping for new ways of functioning. Life is intelligent, not clairvoyant. But the crucial point to see is that even trial-and-error search is still essentially teleological and normative in character. Searches are *aimed at* particular preferred states, and trials are *evaluated* accordingly.

5. The main rival to functionalism is *eliminativism* (Churchland, 1995; Stich, 1996)---the doctrine that teleology and normativity have no objective existence in nature at all, either in brains or elsewhere. However, since we have seen in the last two sections that the putative reduction underpinning the claim of elimination does not in fact go through, I shall not give this position any further consideration here.

6. Of course, differences in degree can also give rise to differences in kind, as we shall see in Section 5, below. Clearly there is something special about *human* brains, since we have capacities that no other organisms possesses. This seems to have to do with fine motor coordination between eye and hand and within the vocal tract, giving rise to technology and

language. The latter capacity, in turn, allows us to imagine non-actual states of affairs and manipulate their mental representations in a way that no other organism can. Out of this ability has then emerged abstract thought, as well as the ability to imagine other perspectives than one's own, which is the basis of moral feeling. By no means do I wish to minimize the radical nature of this discontinuity. I merely wish to stress, in the present context, that specifically human forms of normativity rest on a foundation of generic biological normativity.

7. For further references, as well as discussion of the philosophical significance of this literature, see Barham (2000, 2002a).

References

Albrecht-Buehler, G. (1990) In defense of "nonmolecular" cell biology. *International Review of Cytology*, **120**,191--241.

Albrecht-Buehler, G. (2000) Cell intelligence. www.basic.northwestern.edu/g-buehler/cellint0.htm

Alt, W. (1994) Cell motion and orientation: theories of elementary behavior between environmental stimulation and autopoietic regulation. In *Frontiers in Mathematical Biology*, ed. S.A. Levin, pp. 79--101. Berlin: Springer-Verlag.

Anderson, P.W. (1994). More is different. In *A Career in Theoretical Physics*, pp. 1--4. Singapore: World Scientific. (Originally published in *Science*, 1972, **177**, 393--396.)

Anstey, P. (2001) Boyle against thinking matter. In *Late Medieval and Early Modern Corpuscular Matter Theories,* ed. C. Lüthy, J.E. Murdoch, and W.R. Newman, pp. 483--514. Leiden: Brill.

Auyang, S.Y. (1995) *How Is Quantum Field Theory Possible?* New York: Oxford University Press.

Auyang, S.Y. (1998) *Foundations of Complex-System Theories in Economics, Evolutionary Biology, and Statistical Physics.* Cambridge: Cambridge University Press.

Barbieri, M. (2002) *The Organic Codes: An Introduction to Semantic Biology.* Cambridge: Cambridge University Press.

Barham, J. (1996) A dynamical model of the meaning of information. *BioSystems,* **38**, 235--241.

Barham, J. (2000) Biofunctional realism and the problem of teleology. *Evolution and Cognition,* **6**, 2--34.

Barham, J. (2002a) Theses on Darwin. *Rivista di Biologia/Biology Forum,* **95**, 115--147.

Barham, J. (2002b) Intrinsic function. In preparation.

Barkai, N. and Leibler, S. (1997) Robustness in simple biochemical networks. *Nature,* **387**, 913--917.

Bar-Yam, Y. (1997) *Dynamics of Complex Systems.* Reading, MA: Addison-Wesley.

Batterman, R.W. (2002) *The Devil in the Details: Asymptotic Reasoning in Explanation, Reduction, and Emergence.* New York: Oxford University Press.

Bohr, N. (1987) Light and life revisited. In N. Bohr, *The Philosophical Writings of Niels Bohr, Vol. III: Essays 1958--1962 on Atomic Physics and Human Knowledge,* pp. 23--29. Woodbridge, CT: Ox Bow Press. (Written in 1962; originally published in English translation in 1963.)

Cao, T.Y. (1997) *Conceptual Developments of 20th Century Field Theories.* Cambridge: Cambridge University Press.

Cao, T.Y. (1998) Monism, but not through reductionism. In *Philosophies of Nature: The Human Dimension,* ed. R.S. Cohen and A.I. Tauber, pp. 39--51. Dordrecht, Holland: Kluwer Academic.

Carlson, J.M. and Doyle, J. (2002) Complexity and robustness. *Proceedings of the National Academy of Sciences (USA),* **99**, 2538--2545.

Chalmers, D. (1996) *The Conscious Mind: In Search of a Fundamental Theory.* New York: Oxford University Press.

Churchland, P.M. (1995) *The Engine of Reason, the Seat of the Soul.* Cambridge, MA: Bradford Books/MIT Press.

Clegg, J.S. (2001) Cryptobiosis---a peculiar state of biological organization. *Comparative Biochemistry and Physiology Part B*, **128**, 613--624.

Dawkins, R. (1996) *Climbing Mount Improbable.* New York: W.W. Norton & Company.

Dembski, W.A. (1998) *The Design Inference: Eliminating Chance through Small Probabilities.* Cambridge: Cambridge University Press.

Denbigh, K.G. (1975) *An Inventive Universe.* New York: Braziller.

Dennett, D.C. (1991) *Consciousness Explained.* Cambridge, MA: Bradford Books/MIT Press.

Dennett, D.C. (1995) *Darwin's Dangerous Idea.* New York: Simon & Schuster.

Depew, D.J. and Weber, B.H. (1998) What does natural selection have to be like in order to work with self-organization? *Cybernetics and Human Knowing,* **5**, 18--31.

Dresden, M. (1998) Fundamentality and numerical scales---diversity and the structure of physics. *American Journal of Physics,* **66**, 468--482.

Eden, M. (1967) Inadequacies of neo-Darwinian evolution as a scientific theory. In *Mathematical Challenges to the Neo-Darwinian Interpretation of Evolution,* ed. P.S. Moorhead and M.M. Kaplan, pp. 5--19. Philadelphia: Wistar Institute Press.

Elsasser, W.M. (1998) *Reflections on a Theory of Organisms.* Baltimore: Johns Hopkins University Press. (Originally published in 1987.)

Flyvbjerg, H., Bak, P., Jensen, M.H., and Sneppen, K. (1995) A self-organized critical model for evolution. In *Modelling the Dynamics of Biological Systems,* ed. E. Mosekilde and O.G. Mouritsen, pp. 269--288. Berlin: Springer.

Fontana, W. and Buss, L.W. (1996) The barrier of objects: from dynamical systems to bounded organizations. In *Boundaries and Barriers: On the Limits of Scientific Knowledge,* ed. J.L. Casti and A. Karlqvist, pp. 55--115. Reading, MA: Addison-Wesley.

Frauenfelder, H. and Wolynes, P.G. (1994) Biomolecules: where the physics of complexity and simplicity meet. *Physics Today,* **47**(2), 58--64.

Frauenfelder, H., Sligar, S.G., and Wolynes, P.G. (1991) The energy landscapes and motions of proteins. *Science,* **254**, 1598--1603.

Frauenfelder, H., Wolynes, P.G., and Austin, R.H. (1999) Biological physics. *Reviews of Modern Physics,* **71**, S419--S430.

Fröhlich, F. and Hyland, G.J. (1995) Fröhlich coherence at the mind-brain interface. In *Scale in Conscious Experience,* ed. J. King and K.H. Pribram, pp. 407--438. Mahwah, NJ: Lawrence Erlbaum Associates.

Gabius, H.-J. (2000) Biological information transfer beyond the genetic code: the sugar code. *Naturwissenschaften,* **87**, 108--121.

Georgi, H. (1989) Effective quantum field theories. In *The New Physics,* ed. P. Davies, pp. 446--457. Cambridge: Cambridge University Press.

Godfrey-Smith, P. (1996) *Complexity and the Function of Mind in Nature.* Cambridge: Cambridge University Press.

Gordon, R. (1999) *The Hierarchical Genome and Differentiation Waves,* 2 vols. Singapore: World Scientific.

Ho, M.-W., Haffegee, J., Newton, R., Zhou, Y.-M., Bolton, J.S., and Ross, S. (1996) Organisms as polyphasic liquid crystals. *Bioelectrochemistry and Bioenergetics,* **41**, 81--91.

Ho, M.-W. (1997) Towards a theory of the organism*. Integrative Physiological and Behavioral Science,* **32**, 343--363.

Ho, M.-W. (1998) *The Rainbow and the Worm: The Physics of Organisms,* 2nd ed. Singapore: World Scientific.

Hochachka, P.W. (1999) The metabolic implications of intracellular circulation. *Proceedings of the National Academy of Sciences (USA),* **96**, 12233--12239.

Icke, V. (1995) *The Force of Symmetry.* Cambridge: Cambridge University Press.

Jackson, R.C. (1993) The kinetic properties of switch antimetabolites. *Journal of the National Cancer Institute,* **85**, 539--545.

Jain, S. and Krishna, S. (2001) A model for the emergence of cooperation, interdependence, and structure in evolving networks. *Proceedings of the National Academy of Science (USA),* **98**, 543--547.

Jeong, H., Tombor, B., Albert, R., Oltvai, Z.N., and Barabási, A.-L. (2000) The large-scale organization of metabolic networks. *Nature,* **407**, 651--654.

Jonas, H. (1982) *The Phenomenon of Life: Toward a Philosophical Biology.* Chicago: Phoenix Books/University of Chicago Press. (Reprint ed.; originally published, New York: Harper & Row, 1966.)

Jonker, C.M., Snoep, J.L., Treur, J., Westerhoff, H.V., and Wijngaards, W.C.A. (2002) Putting intentions into cell biochemistry: an artificial intelligence perspective. *Journal of Theoretical Biology,* **214**, 105--134.

Kauffman, S.A. (1993) *The Origins of Order: Self-Organization and Selection in Evolution.* New York: Oxford University Press.

Kirschner, M., Gerhart, J., and Mitchison, T. (2000) Molecular "vitalism." *Cell,* **100**, 17--88.

Kurzweil, R. (1999) *The Age of Spiritual Machines: When Computers Exceed Human Intelligence.* New York: Viking.

Lauffenburger, D.A. and Horwitz, A.F. (1996) Cell migration: a physically integrated molecular process. *Cell*, **84**, 359--369.

Laughlin, R.B. and Pines, D. (2000). The theory of everything. *Proceedings of the National Academy of Sciences (USA)*, **97**, 28--31.

Laughlin, R.B., Pines, D., Schmalian, J., Stojković, B.P., and Wolynes, P. (2000) The middle way. *Proceedings of the National Academy of Sciences (USA),* **97**, 32--37.

Laughlin, R.B., Lonzarich, G.G., Monthoux, P., and Pines, D. (2001) The quantum criticality conundrum. *Advances in Physics,* **50**, 361--365.

Layzer, D. (1990) *Cosmogenesis.* New York: Oxford University Press.

Lecomte du Noüy, P. (1948) *The Road to Reason.* New York: Longmans, Green and Co. (Originally published as *L'homme devant la science.* Paris: Flammarion, 1939.)

Li, K.-H. (1992) Coherence in physics and biology. In *Recent Advances in Biophoton Research and Its Applications,* ed. F.-A. Popp, K.-H. Li, and Q. Gu, pp. 113--155. Singapore: World Scientific.

Locke, J. (1975) *An Essay concerning Human Understanding,* ed. P.H. Nidditch. Oxford: Clarendon Press. (Originally published in 1689.)

Loewenstein, W.R. (1999) *The Touchstone of Life.* New York: Oxford University Press.

Mayr, E. (1982). *The Growth of Biological Thought.* Cambridge, MA: Harvard University Press.

McCann, E. (1994) Locke's philosophy of body. In *The Cambridge Companion to Locke,* ed. V. Chappell, pp. 56--88. Cambridge: Cambridge University Press.

Mikulecky, D.C. (1995) Topological determinants of dynamical molecular properties: a network thermodynamic approach. *Journal of Molecular Structure (Theochem),* **336**, 279--292.

Mikulecky, D.C. (1996) Complexity, communication between cells, and identifying the functional components of living systems: some observations. *Acta Biotheoretica*, **44**, 179--208.

Millikan, R.G. (1998) In defense of proper functions. In *Nature's Purposes: Analyses of Function and Design in Biology,* ed. C. Allen, M. Bekoff, and G. Lauder, pp. 295--312. Cambridge, MA: Bradford Books/MIT Press. (Originally published in *Philosophy of Science,* 1989, **56**, 288--302.)

Moreno Bergareche, A. and Ruiz-Mirazo, K. (1999) Metabolism and the problem of its universalization. *BioSystems,* **49**, 45--61.

Pattee, H.H. (1982) Cell psychology: an evolutionary approach to the symbol-matter problem. *Cognition and Brain Theory*, **5**, 325--341.

Petty, H.R. (2000) Oscillatory signals in migrating neutrophils: effects of time-varying chemical and electrical fields. In *Self-Organized Biological Dynamics and Nonlinear Control*, ed., J. Walleczek, pp. 173--192. Cambridge: Cambridge University Press.

Petty, H.R. and Kindzelskii, A.L. (2001) Dissipative metabolic patterns respond during neutrophil transmembrane signaling. *Proceedings of the National Academy of Sciences (USA)*, **98**, 3145--3149.

Pinker, S. (1997) *How the Mind Works.* New York: Norton.

Polanyi, M. (1969) Life's irreducible structure. In M. Polanyi, *Knowing and Being,* pp. 225--239. Chicago: University of Chicago Press. (Originally published in *Science,* 1968, **160**, 1308--1312.)

Pollack, G.H. (2001) *Cells, Gels and the Engines of Life.* Seattle, WA: Ebner & Sons.

Ravasz, E., Somera, A.L., Mongru, D.A., Oltvai, Z.N., and Barabási, A.-L. (2002) Hierarchical organization of modularity in metabolic networks. *Science,* **297**, 1551--1555.

Rizzotti, M. (1996). Defining life. In *Defining Life*, ed. M. Rizzotti, pp. 1--7. Padua, Italy: University of Padova (sic).

Rosen, R. (1991) *Life Itself: A Comprehensive Inquiry into the Nature, Origin, and Fabrication of Life.* New York: Columbia University Press.

Rosen, R. (2000) *Essays on Life Itself.* New York: Columbia University Press.

Savageau, M.A. (1996) A kinetic formalism for integrative molecular biology: manifestation in biochemical systems theory and use in elucidating design principles for gene circuits. In *Integrative Approaches to Molecular Biology,* ed. J. Collado-Vides, B. Magasanik, and T.F. Smith, pp. 115--146. Cambridge, MA: MIT Press.

Schoffeniels, E. (1976) *Anti-Chance.* Oxford: Pergamon. (Originally published as *L'anti-hasard*, 2nd ed. Paris: Gauthier-Villars, 1975.)

Schrödinger, E. (1992) What is life?, in *What Is Life? with Mind and Matter and Autobiographical Sketches,* pp. 1--90. Cambridge: Cambridge University Press. (Originally published in 1944.)

Schweber, S.S. (1997) The metaphysics of science at the end of a heroic age. In *Experimental Metaphysics,* ed. R.S. Cohen, M. Horne, and J. Stachel, pp. 171--198. Dordrecht, Holland: Kluwer Academic.

Searle, J.R. (1992). *The Rediscovery of the Mind.* Cambridge, MA: Bradford Books/MIT Press.

Srere, P.A. (1994) Complexities of metabolic regulation. *Trends in Biochemical Sciences,* **19**, 519--520.

Srere, P.A. (2000) Macromolecular interactions: tracing the roots. *Trends in Biochemical Sciences,* **25**, 150--153.

Stadler, P.F. (1995) Towards a theory of landscapes. In *Complex systems and binary networks,* ed. R. López-Peña, R. Capovilla, R. García-Pelayo, H. Waelbroeck, and F. Zertuche, pp. 78--163. Berlin: Springer.

Stich, S.P. (1996) *Deconstructing the Mind.* Oxford: Oxford University Press.

Strahl, B.D. and Allis, C.D. (2000) The language of covalent histone modifications. *Nature,* **403**, 41--45.

Surrey, T., Nédélec, F., Liebler, S., and Karsenti, E. (2001) Physical properties determining self-organization of motors and microtubules. *Science,* **292**, 1167--1171.

Thirring, W. (1995). Do the laws of nature evolve? In *What Is Life? The Next Fifty Years,* ed. M.P. Murphy and L.A.J. O'Neill, pp. 131--136. Cambridge: Cambridge University Press.

Unger, P. (2002) Free will and scientiphicalism. *Philosophy and Phenomenological Research,* **65**, 1--25.

Vertosick, F.T., Jr. (2002). *The Genius Within: Discovering the Intelligence of Every Living Thing.* New York: Harcourt, Inc.

Vitiello, G. (2001) *My Double Unveiled: The Dissipative Quantum Model of Brain.* Amsterdam/Philadelphia: John Benjamins.

Walleczek, J. (2000a) The frontiers and challenges of biodynamics research. In *Self-Organized Biological Dynamics and Nonlinear Control,* ed. J. Walleczek, pp.1--11. Cambridge: Cambridge University Press.

Walleczek, J. (2000b).Changing paradigms in biomedicine: implications for future research and clinical applications. In *Self-Organized Biological Dynamics and Nonlinear Control,* ed. J. Walleczek, pp. 409--420. Cambridge: Cambridge University Press.

Watterson, J.G. (1991a) The interactions of water and proteins in cellular function. In *Progress in Molecular and Subcellular Biology,* vol. 12, ed. P. Jeanteur, Y. Kuchino, W.E.G. Müller, and P.L. Paine, pp. 113--134. Berlin: Springer-Verlag.

Watterson, J.G. (1991b) Role of water in cell function. *Biophysics,* **36**, 1--26.

Watterson, J.G. (1997) The pressure pixel---unit of life? *BioSystems,* **41**, 141--152.

Watterson, J.G. (2001) Enzyme function: random events or coherent action? unpublished manuscript.

Webster, G. and Goodwin, B. (1996) *Form and Transformation: Generative and Relational Principles in Biology.* Cambridge: Cambridge University Press.

Whitesides, G.M. and Grzybowski, B. (2002) Self-assembly at all scales. *Science,* **295**, 2418--2421.

Wilson, M.D. (1979) Superadded properties: the limits of mechanism in Locke. *American Philosophical Quarterly,* **16**, 143--150.

Wright, L. (1998) Functions. In *Nature's Purposes: Analyses of Function and Design in Biology,* ed. C. Allen, M. Bekoff, and G. Lauder, pp. 51--78. Cambridge, MA: Bradford Books/MIT Press. (Originally published in *Philosophical Review,* 1973, **82**, 139--168.)

Wu, T.-M. (1994) Fröhlich's theory of coherent excitation---a retrospective. In *Bioelectrodynamics and Biocommunication,* ed. M.-W. Ho, F.-A. Popp, and U. Warnke, pp. 387--409. Singapore: World Scientific.

Yates, F.E. (1994). Order and complexity in dynamical systems: homeodynamics as a generalized mechanics for biology. *Mathematical and Computer Modelling*, **19**, 49--74.

Yi, T.-M., Huang, Y., Simon, M.I., and Doyle, J. (2000) Robust perfect adaptation in bacterial chemotaxis through integral feedback control. *Proceedings of the National Academy of Sciences (USA),* **97**, 4649--4653.

Yockey, H.P. (1992) *Information Theory and Molecular Biology.* Cambridge: Cambridge University Press.

Yolton, J.W. (1983). *Thinking Matter: Materialism in Eighteenth-Century Britain.* Minneapolis: University of Minnesota Press.

Zhou, T., Carlson, J.M., and Doyle, J. (2002) Mutation, specialization, and hypersensitivity in highly optimized tolerance. *Proceedings of the National Academy of Sciences (USA),* **99**, 2049--2054.