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## The biogenic approach to cognition

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**Abstract** After half a century of cognitive revolution we remain far from agreement about what cognition is and what cognition does. It was once thought that these questions could wait until the data were in. Today there is a mountain of data, but no way of making sense of it. The time for tackling the fundamental issues has arrived. The biogenic approach to cognition is introduced not as a solution but as a means of approaching the issues. The traditional, and still predominant, methodological stance in cognitive inquiry is what I call the anthropogenic approach: assume human cognition as the paradigm and work 'down' to a more general explanatory concept. The biogenic approach, on the other hand, starts with the facts of biology as the basis for theorizing and works 'up' to the human case by asking psychological questions as if they were biological questions. Biogenic explanations of cognition are currently clustered around two main frameworks for understanding biology: self-organizing complex systems and autopoiesis. The paper describes the frameworks and infers from them ten empirical principles—the biogenic 'family traits'—that constitute constraints on biogenic theorizing. Because the anthropogenic approach to cognition is not constrained empirically to the same degree, I argue that the biogenic approach is superior for approaching a general theory of cognition as a natural phenomenon.

**Keywords** Cognition · Theory · Explanation · Biology of cognition

### Background

Bechtel and colleagues are surely right when they claim that the three main underlying objectives of the

multidisciplinary effort called 'cognitive science' is to provide an explanation of what cognition is, what cognition does, and how cognition works (Bechtel et al. 1998). If so, then it must be admitted that, despite half a century of cognitive revolution, very little progress has been made on the first and second questions, the answers to which are interdependent. Traditional computationalists (classical or connectionist) claim that cognition involves the transformation of (external or internal) inputs to (overt or covert) outputs through the mediation of representations (whatever they might prove to be). Drawing a principled distinction on this basis between what brains do and, say, thermostats do have generated a small cottage industry. The ranks of anti-representationalists, once marginal, are growing. Those who favour an embodied cognition approach tend to emphasize dynamical perception–action coupling in the context of an environment as the basis of cognition, but that still leaves the question of how characterize the function itself unanswered.

Haugeland (1997) suggests, plausibly, that the cognitive revolution tended to bracket the what-it-is issue to get on with the job of investigating how it works. Many apparently assumed that as empirical data accumulated, an appropriate characterization would somehow present itself. Now, as the data assume oceanic proportions, some are no longer so sure (Hardcastle 2001). What cannot be denied is that nothing even remotely approaching consensus exists regarding what sorts of natural systems are cognitive and what sorts are not, to say nothing of artefacts. The proposals run literally the phylogenetic gamut, from the simplest to the most complex organisms: even unicellular organisms have their advocates (Jennings 1905/1962; Washburn 1936; di Primio et al. 2000; Margulis 2001). Surely, this high degree of uncertainty about how the central object of inquiry is even to be identified, much less explained—after hundreds of years of investigation—is unique in the history of science.

The purpose of this paper is not to propose answers to the what-it-is and what-it-does questions regarding

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cognition but, rather, to examine in detail a particular way of approaching such questions. The aim is to stimulate debate about the correct way to proceed to answers. It seems to me that there are, generally speaking, two ways of approaching cognition. The approaches are defined by a methodological assumption relating to the starting point of inquiry that is rarely explicit and is sometimes denied. Do we start from the human case and work our way 'down' to a more general explanatory concept, or do we start from the facts of biology and work our way 'up' to the human case? I call the tradition that takes the human case as its starting point for the study of cognition the *anthropogenic* approach (from the Greek; literally, human + birth, origin). The tradition that starts with the principles of biology is the *biogenic* (life + birth, origin) approach.<sup>1</sup>

It is important to emphasize that the distinction relates to a strategic calculation, not (necessarily) to a preference about where on the phylogenetic tree natural cognition is to be found. An investigator adopting an anthropogenic approach assumes that the features of human cognition—derived from introspective experience, human behaviour, or the science of the human brain—are the most plausible and potentially fruitful (possibly the only) guide to understand the phenomenon of cognition generally. Anthropogenic approaches assume, to a greater or lesser extent, that human psychological attributes are the hallmarks of cognition and ask what sort of biological or evolutionary story might account for them. These attributes may include beliefs, desires and other so-called 'propositional attitudes,' rational problem solving, the ability to form concepts and to generalize from particular instances to categories, abstract and/or symbolic ideation, language, episodic memory, theory of mind, the ability to represent the absent, phenomenal consciousness, reflexive awareness, and so on. Investigators vary considerably both in relation to the attributes they take to be roughly diagnostic of cognition and how widely or narrowly they construe those attributes.

By contrast, an investigator adopting a biogenic approach assumes that the principles of biological organization and the requirements of survival and reproduction present the most productive route to a general understanding of the principles of cognition. Cognition, whatever else it may be in the future, is naturally a biological process and a biological function. Functional biological processes—such as nutrient circulation, respiration, ingestion, digestion, and elimination—cannot be understood, apart from the context of living organization. Biogenic approaches thus ask psy-

chological questions as if they were biological ones. For example, what is it that biological systems do such that they might require cognition? Here too, investigators differ about the features of animate organization, or the biological business of making a living, that are most important to characterizing and understanding cognition. Evolutionary epistemologists, for example, emphasize trial-and-error problem solving subjected to natural selection (Popper 1965/1972; Campbell 1974). Others draw out the implications of organism–environment interaction in various ways (Gibson 1979; Varela et al. 1991; Bickhard 1998; Christensen and Hooker 2000). For still others, it is the dynamic imperatives of maintaining not only order but also a special sort of self-producing organization far from thermodynamic equilibrium (Maturana 1970/1980; Maturana and Varela 1973/1980; La Cerra and Bingham 2002; Goodson 2003).

I develop the anthropogenic/biogenic distinction in more detail elsewhere (Lyon 2005). Suffice to say, most approaches to cognition throughout history have been anthropogenic, for obvious reasons. We have access to our own minds and can communicate our experience of mentality to others, so human cognition is the logical place to start. What I will do here is sketch the characteristics of a neglected alternative, the biogenic family of cognitive explanation, and demonstrate its advantages for characterizing cognition as a natural phenomenon.

'Family' is employed here in two ways, biological and philosophical. In biological classification, a family is a cluster of similar or closely related genera (plural of genus), which in turn comprise similar or closely related species. Within the biogenic and anthropogenic families are general approaches to cognition with delineable characteristics, within which are specific explanatory proposals or frameworks. The philosophical meaning I intend is similar to Wittgenstein's (1953/1994) notion of 'family resemblance', a class of phenomena that share one or more similarities to varying degrees of strength but which may elude definition in terms of necessary and sufficient conditions. Family traits, in ordinary meaning, serve as constraints on identification (e.g., this is the family build, that is the family nose). As invoked here they serve as constraints on explanation and parameters that must be accommodated to some degree or other in an adequate theory of cognition.

The traits of the biogenic family—of which I identify ten—are derived from the genera, which on my reckoning are principally two: self-organizing complex systems (SOCS) and autopoiesis. The genera differ from one another in their points of departure or emphasis. Artificial life is not counted separately because research conducted under this rubric usually falls within one or more of the frameworks listed. Within each genus are species of explanation, specific hypotheses or conceptual frameworks that also differ subtly from one another. Collectively, the biogenic family traits provide a rather hefty set of constraints on any explanation of cognition pursued within the approach. This set of empirical

<sup>1</sup>'Anthropogenic' is an adjective long used in plant ecology to refer to plants introduced by humans; it increasingly refers to climate change associated with human activity. 'Biogenic' is used in geology to refer to the origins of certain rock strata. Limestone is biogenic, for example, because its origin is material that once formed part of living organisms. I am indebted to Jon Opie for suggesting that I devise neologisms for this distinction and to my husband, Richard Bradshaw, for finding them.

constraints, I argue, is the major strength of biogenic approaches to cognition generally, particularly when compared to the traits of the anthropogenic family. For this reason the biogenic approach is better equipped to address what-it-is and what-it-does issues.

The paper is structured broadly as follows. Section 2 describes the anthropogenic family traits and argues that, collectively, they not only constrain cognitive explanations very little but also generate a number of problems. Section 3 describes the different biogenic genera and is divided into two subsections corresponding to them. Self-organizing complex systems, as the dominant approach and most populous genus, is described in greatest detail. The biogenic ‘family traits’ are inferred at relevant points in the discussion. Section 4 compares the anthropogenic and biogenic sets of constraints and discusses the advantages of the biogenic approach for developing a general theory of cognition as a natural phenomenon.

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### The anthropogenic ‘family’ traits

In this section I will derive the main anthropogenic family traits as provided within the cognitivist paradigm, which will serve as the contrast case for the biogenic approach. I hope to show that the anthropogenic family traits do not constrain theorizing about cognition very much at all. In fact, some principles give rise to difficulties that remain unresolved. Before we examine the foundations of cognitivism, however, let us begin with the first and second anthropogenic principles, the cornerstones of the modern program for naturalizing the mind.

*Anthropogenic principle #1—Brain: Cognition is implemented or instantiated in a brain and/or nervous system.*

An anthropogenic hypothesis need not make explicit reference to neuroscientific data, but at some point in the articulation of a general claim about cognition a gesture in the direction of this literature is considered good practice. In conceptual philosophical discussions the base-covering locution often takes the form of something like, ‘whatever our best (name the science) tells us about  $(x, y, z)$ ’. An anthropogenic explanation need not be a variation on mind-brain identity theory or type physicalism. Substrate-neutral brands of functionalism (multiple realizability theses) usually gesture in the direction of neuroscience, e.g., in the ubiquitous references in discussions of pain to the registration in the brain of ‘c-fibres firing’.

The problem with this constraint is that it constrains very little. In many philosophical accounts it appears to serve principally as a ‘sign of the cross’ to ward off substance dualism. The brain and central nervous

system are involved in far more than cognition, however it is construed. The brain controls just about all of the body’s functioning (even if we acknowledge the relative independence of the enteric nervous system), and a high degree of interdependence makes it difficult to tease out the purely cognitive from the putatively non-cognitive aspects of brain function. The physiological reality of interdependence is the basis of burgeoning inquiry into the placebo effect since the US National Institutes of Health launched a major research initiative (NIH 2001).

Moreover, the principle rests on a criterion—that behaviour should only be construed as cognitive in the presence of a nervous system of ‘sufficient complexity’—which was proposed by Lamarck two centuries ago (Bateson 1979) and largely unquestioned since. It is not a criterion that Darwin appears to have endorsed (Darwin 1874/1909; Crist 2002), and recent discoveries about the life world of the very small, enabled by instruments and methods of undreamed-of precision and subtlety, arguably raise doubts about its continuing utility. For example, what is believed to be the simplest metazoan visual system yet discovered was recently characterized in the larvae of a type of jellyfish, one species of which (the box jellyfish) is the sometimes-fatal scourge of swimmers off the northeastern coast of Australia (Nordstrom et al. 2003). The visual system does not rely on neurons or axonal connections between different cell types or tissue layers. In short, there does not appear to be a mechanism for the exchange of information between cell and tissue types characteristic of animals with nervous systems, yet the behaviour of the larvae is indistinguishable from that of related cnidarians possessing neuron-based vision. The adult form of the box jellyfish has neurons but no brain; nevertheless, it is capable of surprisingly complex differential behaviour. Now we can declare, as did Lamarck, that nothing without a nervous system or a brain can be genuinely cognitive, but whereas this claim previously could be made without argument, I suggest this is no longer the case. It certainly cannot be assumed in the absence of a general theory of cognition. Although it restricts where it is, Lamarck’s criterion certainly goes no distance toward addressing what-it-is and what-it-does issues related to cognition.

The obvious role of cognition in the generation of behaviour provides the second anthropogenic principle:

*Anthropogenic principle #2—Behaviour: Cognition has an important role in generating adaptive behaviour.*

It is clear that this principle, too, constrains very little. Behaviourism in general and radical behaviourism in particular pursued a science of behaviour for half a century without explicit reference to cognition. It was the re-admission of causally efficacious inner states in more explicit terms than ‘hidden variables’ that gave the cognitive revolution its name. The evisceration of

Skinnerian behaviourism by Chomsky (1981) was, famously, a turning point. This is where cognitivism comes in.

The cognitivist paradigm is intrinsically anthropogenic, despite a functionalist agenda prepared to admit not only nonhuman species but also intelligent machines into what Lockery calls “the psychological club” (Lockery 1989). Again, we are talking about starting assumptions in defining the problem space. Several broad movements contributed to the initial formulation of cognitivism, which arguably continue to shape the paradigm: computer science, information and communication theory, Chomskyan linguistics, and intentional psychology as interpreted mainly through Anglo-American analytic philosophy (Gardner 1985; Dupuy 2000). All of these movements were anthropogenic. In other words, they took one or more features of human cognition—indeed, often the most complex instances of human cognition—as the starting point for investigating cognition.

As is well known, Turing conceived the idea of a mechanical computer to perform complex mathematical calculation, a task that, at the time, was regarded as distinctively human and was performed by people who were called ‘computers’ (Turing 1936; Copeland 1996). At its simplest, the universal Turing machine is a device to transform, according to a specified computational function, an input into an output. The idea of the universal Turing machine proved extraordinarily powerful, and its potentially wide application became the inspiration not only for Shannon and Weaver’s mathematical theory of communication (Shannon and Weaver 1949) but also for the McCulloch–Pitts model of the neuron as a simple digital computing device that could work in larger ensembles of units (McCulloch and Pitts 1943). These three developments—the Turing machine, information theory, and the McCulloch–Pitts neuron—were crucial to the birth of artificial intelligence and the goal of ‘designing a mind’ that lay at the heart of the cognitive revolution (Miller 2003). Simulating cognition, it was presumed, would reveal the principles of natural cognition. The Turing machine thus provides us with the third anthropogenic principle, which continues to be accepted despite the fading charisma of its original inspiration.

*Anthropogenic principle #3—Information processing: Cognition involves the computational transformation of inputs, from within the system or from the environment, leading to an output that is behaviourally overt or covert, that is, internal to the system.*

Famously, thermostats and guided missiles meet this criterion. As Floridi (2004) points out, “informational concepts are so powerful that, given the right level of analysis, anything can be presented as an information system” (p 566), an argument first advanced by Searle (1981) in the Chinese Room thought experiment.

Thanks in part to the generality of the information processing approach, for a very long time the empirical ballast for much theorizing about cognition was highly selective, decidedly light and rested on thought experiments of dubious ultimate value (Hull 2001). That the embodied cognition movement did not get legs until the fifth decade of the cognitive revolution is testimony to this fact. To be sure, cybernetics provided a biologically respectable (if not biologically inspired) model of control systems based on positive and negative feedback, but Shannon and Weaver’s information theory notoriously had absolutely nothing to say about the most biologically salient aspect of human communication: meaning.

The putative gold standard of machine intelligence, the Turing test, is based on human language and the ability to deceive a person in a conversation. Chomsky’s challenge to the behaviourist paradigm, too, was on the basis of language. Language, needless to say, is the foundation of, and provides the existence proof for, all of humankind’s most complex cognitive capacities, including reflexive consciousness. If a *Scala Naturae* view of the living world is sustainable at all (and I do not believe it is), human symbol use and the culture that flows from it are typical justifications.<sup>2</sup>This provides the fourth anthropogenic principle:

*Anthropogenic principle #4—Complex traits: An adequate theory of cognition must account for complex behavioural traits such as language, abstract thinking, beliefs, desires, phenomenal consciousness, and culture.*

Again, the nature of the constraint is ambiguous. This is mainly because nothing approaching consensus exists as to how the relevant complex traits should be characterized such that they might be identified in nonhuman species and entities. This is as true of behaviour in general (see especially, Keijzer 2001, pp 15–58), as it is of complex behavioural traits such as rationality (e.g., Charniak 1986), consciousness (e.g., Hardcastle 2001), language (e.g., Dennett 1989; Prete 2004) and culture (e.g., de Waal 2001; Byrne et al. 2004).

The fifth and sixth anthropogenic principles are related. If the Turing test presented a goal for simulated cognition, analytic philosophy suggested the semantic units for computational transformation: beliefs, desires and other content-bearing ‘propositional attitudes’. Commonsense or folk psychology provided the basis, and Brentano’s thesis provided the necessary level of abstraction. Brentano’s thesis holds that intentionality, or “the mind’s directedness on the world,” is the dis-

<sup>2</sup>An example: “As our species designation—*sapiens*—suggests, the defining attribute of human beings is an unparalleled cognitive ability. We think differently from all other creatures on earth, and we can share those thoughts with one another in ways that no other species even approaches. In comparison, the rest of our biology is almost incidental” (Deacon 1997).

tinguishing ‘mark of the mental’ (Crane 1998, p 250). Based on human interpretive practice, folk psychology is anthropogenic almost by definition. Brentano’s concept of intentionality, borrowed from (anthropogenic) scholastic philosophers who took for granted the Great Chain of Being, was also based on human experience and advanced at a time when the application of Darwin’s new theory of evolution to psychology was yet to come. Although intentionality now seems to be ubiquitous throughout the biological world (to say nothing of artefacts), it is anthropogenic because of its origins and provides the fifth principle.

*Anthropogenic principle #5—Intentionality: A distinguishing property of cognition is that it is directed toward (or about) some state of affairs in the world.*

If cognitive states are about states of affairs, and that is clearly how it seems to us—we can, after all, think of existing things not present and about things that have never existed—they have a content of some kind. Content, in turn, bears some correspondence relation to the states of affairs about which it is content by definition. The correspondence (which implies nothing about the specific relation) is commonly conceived of as representational. The content of a cognitive state represents a state of affairs; how it does so is another matter. This provides the sixth and final anthropogenic principle.

*Anthropogenic principle #6—Representation: Because it is directed toward a state of affairs, a cognitive state has a representational content.*

While commonly held, these two principles are provisional. Some intentional explanations of cognition that do not embrace computationalism—e.g., in the continental philosophical tradition (e.g., Husserl 1952; Merleau-Ponty 1962)—are constrained neither by belief-desire psychology nor by representationalism. Similarly, theories based on information processing need be constrained neither by belief-desire psychology (Stich 1983; Churchland 1987, 1989; Bechtel and Abrahamsen 1990) nor, in principle, by representationalism (Cliff and Noble 1997). Representationalism, likewise, need not be committed to belief-desire psychology as an explanatory tool. Importantly, the meaning of ‘representation’ is ambiguous and still evolving (Clark 1997a, b; Haselager et al. 2003; Clapin et al. 2004). The meaning of ‘representation’ ranges from meaningful co-variation of cognitive states with changing conditions, the kind of correspondence of which a mechanical device such as a Watt governor is capable (Bechtel 1998), to much richer notions of structural resemblance (O’Brien and Opie 2004).

The major problem for these two principles is how cognitive states come to be ‘about’ anything at all (the

symbol-grounding problem) and how myriad representations are continually and coherently updated as circumstances change in real-time (the frame problem) (Harnad 1993). As Brooks (1991) observed when he introduced the AI community to the heretical idea of “intelligence without representation,” these seemingly intractable problems for engineering intelligence arose from the overriding cognitivist concern with human rationality, human decision making, human problem solving, and human knowledge generation and structuring, processes that were then and still remain ill-characterized and poorly understood. Brooks’ solution to the impasse was to go back to the biological drawing board. In my terminology, he opted to take a biogenic approach to the problem of engineering intelligent machines.

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### **Biogenic genera**

While biogenic approaches to cognition have their roots in the philosophy of Aristotle, they did not truly begin to develop until the birth of biology as a science in the early nineteenth century. Moreover, they did not begin to take shape in any systematic way until the later twentieth century, and even then, only with some difficulty (Lyon 2004). Without widespread scientific acceptance of the meaningful evolutionary continuity of human beings with other animals, which coalesced in the modern synthesis of neo-Darwinism, there is no good reason to presume a biogenic approach would be of any use whatsoever in explaining cognition. In the (anthropogenic) Cartesian picture and the classical *Scala Naturae* view, the presence of cognition—in kind, not merely degree—is what sets humankind apart from the rest of the natural world. The evolutionary principle is thus the *sine qua non* of the biogenic approach. Because evolution by natural selection is the overarching ordering principle of contemporary biology, it provides us with the first of the biogenic family traits.

*Biogenic principle #1—Continuity: Complex cognitive capacities have evolved from simpler forms of cognition. There is a continuous line of meaningful descent. (Note: this does not rule out the emergence of novel capacities with increasing complexity.)*

Anthropogenic approaches to cognition may proceed, and have for millennia, in the absence of evolutionary theory. Thus anthropogenic approaches factor in evolution for scientific plausibility. This factoring can be thorough-going and highly biological (Dretske 1988; Dennett 1991; Hurley 1998; Sterelny 2001) or relatively desultory (e.g., Putnam 1988; Chalmers 1996). The point is that the anthropogenic explanatory agenda is determined by considerations that may or may not be biological in nature. In biogenic approaches, biology determines how inquiry proceeds to explanation.

Biogenic approaches should also be distinguished from embodied cognition. Embodied cognition (EC) is the philosophical movement associated with the belated recognition that knowledge-generating mechanisms (such as we know them) are embodied in an organism (human or otherwise) that is situated or embedded in an environment with which it must continually contend and which, in doing so, it also modifies (Varela et al. 1991; Clark 1997a). Additionally, EC recognizes that the mechanisms of cognition have evolved to assist the organism in its interaction with an environment (see especially Beer 1990; Godfrey-Smith 1996). EC thus holds that cognition cannot be explained adequately if divorced from consideration of the environment with which an organism is coupled. However, in my view EC as a movement is better seen as a necessary philosophical readjustment—one might say the acknowledgement of the bleeding obvious—rather than a research program with particular characteristics, such as classical computationalism. By acknowledging that the only cognitive mechanisms about which we are certain are those that have evolved in biological systems constantly engaged in body-world interactions, EC exhorts us to take prevailing biological knowledge and evolutionary theory seriously. But biology can be taken seriously in all sorts of ways. One need not begin with the principles of biology to ensure at a minimum that one's theory of mind does not contravene those principles.

This is illustrated by the fact that some prominent advocates of evolved and embodied cognition, who take a highly biological approach to the subject, nevertheless retain conceptual frameworks I class as anthropogenic. These include, for example, Clark (1997b), Dennett (1996), Dretske (2000), and Sterelny (2003). All emphasize the importance of the body-world relation in explaining cognition and were part of the necessary attitudinal readjustment in cognitive science of which EC is the flag-bearer, but all have conceptual frameworks grounded more or less in intentional psychology. In summary, while a biogenic approach to cognition is intrinsically embodied, an embodied approach need not be biogenic. One can take a biogenic approach to beliefs and desires as psychological phenomena requiring explanation, for example, without assuming that beliefs and desires are hallmarks of cognition and then building a plausible biological case for how they might have evolved. Again, the anthropogenic/biogenic distinction relates to starting assumptions about the problem space, not to how 'biological' a proposal is.

In the next two subsections, we will look at the main branches of the biogenic family. Each derives its distinctive character from the aspect of biology it emphasizes. The first concentrates on the physics of organisms as complex, dynamic, self-organizing and thermodynamically open systems. The second focuses on the 'biology' of biology, namely, the distinctive self-producing organization of vitality. Species of explanation within each genus, i.e., specific proposals relating to cognition, can be cashed out in weak and strong

versions. The key difference is constitutive. In weak versions, cognition is seen to have an important role in the elaborated feature; it is contributory. In strong versions, cognition is that feature; it is constitutive. The virtue of the strong version is the relative ease of explicating the concept for operational use, but it may be purchased at the cost of precision. The weak version involves delineation of a boundary, which may be drawn in a principled way but requires argument more or less case-by-case, framework-by-framework.

There is a third potential biogenic framework for theorizing about cognition, but as far as I can tell no models have been inspired by it (a possible exception is Brier 2000). Biosemiotics<sup>3</sup> stresses what could be termed the 'intentionality' of biology, the fact that, to paraphrase Howard Pattee (1969), biological molecules are often 'messages', that relay information about their own state, the state of the environment, or the state of the system. The fundamental insight of biosemiotics is that biological phenomena at every level of description, from molecules to organisms, are controlled by 'information', at least in a vague Batesonian sense. As agents of change—initiators, promoters, or intermediate participants in cascades of response—biological macromolecules simultaneously function as carriers and consumers of information. They are, in some as-yet-obscure and controversial<sup>4</sup> sense, 'directed toward', 'indicative of,' possibly even 'about' some state of affairs. Given the immediate circumstances they function to bring the process of which they are a component to one state rather than another, frequently exhibiting causal patterns that are nonlinear and selectionist. The relationship of one molecule to another, while specific and parasitic upon biochemical properties, does not appear to be determined by these properties. Moreover, what a molecule indicates depends on context. There is nothing logically or chemically determined in the relationship of aspartate, say, to the molecular machinery of *Escherichia coli* that captures and brings it into the cell, or induces a change in the rotation of a flagellum.

On the biosemiotic perspective, information usage is not only intrinsic to the process by which organisms adapt, both internally and externally, it is very probably the distinguishing feature of life (Hoffmeyer and Emmeche 1991; Emmeche 1998; Balazs 2004). Hence, advocates sense its potential as a paradigm capable of integrating data and unifying theory on "a vast array of biological phenomena" (Eder and Rembold 1992, p 63).

<sup>3</sup>Biosemiotics should not be conflated with biosemantics, with which it is congenial but not identical. Biosemantics is Millikan's relentlessly biological rendering of intentionality within the content of ongoing anthropogenic debates (Millikan 1989). Biosemiotics, by contrast, is grounded in Jacob von Uexküll's biological theory of meaning, Peircean sign theory and contemporary molecular biology—its leading advocates are, in fact, biologists—and does not engage with analytic philosophical debates.

<sup>4</sup>Whereas some thinkers (e.g., Matthen and Levy 1986) are comfortable ascribing intentionality to macromolecules, others (e.g., Rosenberg 1986) strongly oppose such attribution.

Even more ambitiously, biosemiotics has been proposed as a bridge between the humanities and the sciences (Sebeok 1996). While intriguingly suggestive, biosemiotics remains insufficiently developed to evaluate its usefulness as an approach for theorizing about cognition. Biosemiotics may prove to be a ‘turtles all the way down’ perspective that has the virtue of application at multiple descriptive scales. Just as likely, however, descriptions of information-controlled interactions at the molecular scale may prove to bear the same relation to the explanation of living systems as the mapping of brain functions do to the explanation of mind: absolutely important but (so far) offering little explanatory leverage on the higher-level phenomenon. Among the obvious challenges is clarification of its central concept, information, and explication of the notion of semiosis such that it can perform useful theoretical labour.

### Self-organizing complex systems (SOCS)

The most populous genus of the biogenic family, as well as the dominant approach to A-life (Boden 1996), is what I will call self-organizing complex systems (SOCS). The general thrust of the SOCS approach in relation to cognition is neatly captured in the aphorism coined by La Cerra and Bingham (2002): ‘The first law of psychology is the second law of thermodynamics’. With respect to the Second Law, it is wise to keep in mind two things that make it unusual in the canon of physical law. First, the Second Law is “easily the most difficult and most misunderstood of the concepts of classical physics” (Trefil 2003, p 399), not least because it is rather more ambiguous than is generally thought good for a physical law to be, as is the concept of entropy at its heart. Corning and Kline (1998a, b) claim to have uncovered “at least a dozen definitions” of entropy, classically a measure of disorder. The Second Law is also unusual because it has ‘directionality’ (Trefil 2003), the processes it describes are irreversible, whereas most physical laws do not have an arrow of time (see especially Prigogine 1996). Time’s arrow is widely manifested in living systems. ‘Chronobiology’, a young field, studies biological processes regulated according to the Earth’s daily revolution around the sun (circadian processes) or longer periods (ultradian processes). Complex behavioural patterns apparently are not immune from this sort of temporal regulation (Anolli et al. 2005; Kerepesi et al. 2005).

The Second Law holds that closed physical processes tend toward a state of “increasing (statistical) probability and decreasing order” (one fairly standard rendering of entropy), leading ultimately to thermodynamic equilibrium (von Bertalanffy 1968, p 150). Organisms, by contrast, “maintain themselves in a state of high statistical improbability, of order and organization,” far from thermodynamic equilibrium (ibid.). Organisms do this by importing ‘order’ (energy in the form of matter) from the environment, chemically transforming it via

metabolic processes into useable forms of fuel for the synthesis of biologically important molecules, and exporting ‘disorder’ in the form of waste products of various sorts. This continual exchange of matter and energy—which makes organisms thermodynamically *open systems*<sup>5</sup>—takes place within an environment of constantly shifting parameters: temperature, weather, the availability of food, water, shelter, the chemical profile of the atmosphere, the presence or absence of predators and parasites, and the presence or absence of toxic substances. Organisms adapt to changing circumstance as best they can. With luck, they survive and (hopefully) reproduce.

The most important feature of an open system is the attainment of the steady state, which is maintained “at a distance from true equilibrium”<sup>6</sup> despite continuous and irreversible processes of construction and degeneration (von Bertalanffy 1968, p 149). Among the remarkable characteristics of the processes that maintain an open system in a steady state far from thermodynamic equilibrium is that they are capable of performing work, a feature recently elaborated upon by Kauffman (2000). Another is that the steady state is determined by system parameters (i.e., rates of reaction and transport) rather than initial conditions. The steady state can be reached from different initial conditions (within a range) and be regained after disturbance (again, within a range). In biological systems maintenance of the steady state is commonly identified with homeostasis.<sup>7</sup> Organisms maintain a steady state far from thermodynamic equilibrium via the continual, controlled synthesis of biologically important macromolecules, which simultaneously constitute the system and carry out its metabolic processes. All biological processes that contribute to an organism’s survival—and cognition is clearly such a

<sup>5</sup>Erwin Schrödinger is commonly credited with pointing out the peculiarity of organisms relative to the laws of classical thermodynamics, which ultimately led to the development of nonclassical elaborations such as dissipative structures. In reality, the German theoretical biologist Ludwig von Bertalanffy proposed the idea of a thermodynamically open system in 1940, which forced physicists (and chemists such as Prigogine) to take note. Ironically, Bertalanffy proposed the open system concept as a counter to metaphysical vitalism, only to have his own general system theory tarred with the vitalist brush by reductionists such as Jacques Monod.

<sup>6</sup>‘True equilibrium’ here refers to thermodynamic equilibrium, or total molecular disorder, which is death for a living system. The phonemic similarity but conceptual antonymity of thermodynamic equilibrium and metabolic balance maintained by homeostasis, which is often referred to in terms of equilibrium, is an unfortunate fact of interdisciplinary history and is an object lesson in the problems of overlapping terminologies.

<sup>7</sup>Homeostasis is defined as “the regulation by an organism of the chemical composition of its body fluids and other aspects of its internal environment so that physiological processes can proceed at optimum rates. It involves monitoring changes in the external and internal environments by means of receptors and adjusting the composition of the body fluids accordingly; excretion and (osmotic) regulation are important in this process” (Martin and Hine 2000). Two examples of homeostatic regulation are the acid-base balance and body temperature.

process—contribute to homeostatic regulation. This provides the second principle of the biogenic approach:

*Biogenic principle #2—Control: Cognition directly or indirectly modulates the physico-chemical-electrical processes that constitute an organism.*

Although control is an undisputable biological necessity to which cognition contributes, it points up a problem with SOCS approaches to cognition: a subtle form of question begging that assumes what requires explanation. A kind of slip routinely occurs in the SOCS literature between talk of self-organizing physico-chemical systems and talk of biological systems that suggests the broad explanatory features of both are, in some important way, similar, if not equivalent. They are not. A difference of many magnitudes exists—even at the molecular level—between the order displayed by a self-organizing physical system, such as a hurricane, a convection cell or a Bose-Einstein condensate, and the feedback-controlled functional organization characteristic of all biological systems. Biological organization is a sustained, regulated, locally replicating and globally replicable kind of order that performs work in the service of its own persistence and replication while simultaneously resisting perturbation within a relatively wide range of variation. The suspicion is growing that thermodynamics cannot get us from physical order to biological organization (see especially, Corning and Kline 1998a), not even with the expanded principles of dissipative structures (Prigogine 1996) and related theoretical constructs, such as hypercycles (Eigen and Schuster 1979), organized criticality (Bak 1996), and Kauffman's concept of "the adjacent possible" (Kauffman 2000). Filling in the gaps is not a problem for cognitive science, but theorists building an approach to cognition on SOCS approaches to life should be aware of them.

Clearly, maintenance of the steady state characteristics of biological systems comes at a cost. Energy is constantly expended and must be replenished. The energetic costs of even the simplest biological system are, by any standard, enormous. The amount of "sheer (physical) manipulation" that a single bacterium performs in the course of synthesizing its body mass is nothing short of staggering. The task, which takes 20–30 min, has been compared to 1,000 human beings stringing beads at a rate of one every 5 h, 8 h, a day, 5 days a week, for 35 years (Cairns-Smith 1985, p 19). But the bacterium is not only stringing the beads but manufacturing them as well. At the metazoan level, a shrew must consume roughly three times its body weight every day or starve (Olson 1997, p 127). Cognition enters the picture naturally at the 'front end' of the process, with energy importation. Hence, the third principle:

*Biogenic principle #3—Interaction: Cognition enables the establishment of reciprocal causal relations with an*

*environment, leading to exchanges of matter and energy that are essential to the organism's continued persistence, well-being or replication.*

Energy-acquiring activities—including foraging, food storage and retrieval, patch usage, stealing and concealing food—have long been central to understanding complex behaviour in behavioural ecology and cognitive ethology. In those disciplines, food-focused activities have been important to the project of extracting general principles relating to cognitive function, such as the relation between the size of the hippocampus and memory in food-storing birds (Macphail and Bolhuis 2001), evaluation of predation risk vs. nutritive reward in foraging (Gray 1994), stealing and concealing behaviour, and, more recently, tool use (Tebich and Bshary 2004). By contrast, according to psychologist Morten L. Kringelbach (2004), the cognitive neurosciences have largely ignored the implications of food intake for investigating cognition, despite the fact that it engages and integrates a wide range of motivational, cognitive, and emotional processes of both a basic biological and a culturally conditioned character.

Kringelbach (2004, p 815) argues that even the most highly complex human cognitive capacities have evolved to support "the sustained food intake needed" to maintain human life. The location, identification and evaluation of food sources for desirability and appropriateness (at a minimum, non-toxicity) involves the integration of multiple channels of perception (visual, olfactory, gustatory, and sensual) as well as memory, learning, planning, and prediction.<sup>8</sup> Although sex usually takes top billing in matters hedonic, much of life's pleasure—not merely for humans but for all mammals, and possibly all animals—is food related. In mammals, at least, food intake involves the subtle interaction between homeostatic regulation and hedonic sensory pleasure, the *qualia* (phenomenal qualities) associated with food.<sup>9</sup>

A host of social behaviours—widely held to be a (if not the) major factor in the development of complex cognition—evolved to support food intake. Foremost among these energy-related social behaviours are cooperative foraging and hunting and associated food preparation, which in the human case involved the development of tools, the use of fire, and, very possibly, language. For thousands of years human technological advances largely tracked concern with sustenance, beginning with the development of agriculture and the domestication of animals. Ritual practices developed around planting, harvesting, feasting, food purity, and

<sup>8</sup>Kringelbach points out that relatively slow metabolic processes, in humans at least, means that internal system changes do not swiftly track food intake, thus regulation of eating behaviour requires "sophisticated [neural] mechanisms to learn to predict in advance when a meal should be initiated and terminated" (2004, p 808).

<sup>9</sup>For this reason Kringelbach suggests that food intake in nonhuman mammals may provide good model systems for investigating the neurobiology of phenomenal experience.

taboos (Levi-Strauss 1969), which in turn fuelled art and religion, from the cave paintings of Lascaux to the monumental architecture of Meso-America. Surplus production provided the basis for systems of social and economic exchange that led not only to the development of more complex forms of settlement (Holmes 2004), from villages and towns to sprawling cities (Lawton 2004), but also to symbolic tools like writing and mathematics. Warfare, too, has a food-related dimension, from conflicts over hunting and foraging territories and arable land to slaving campaigns to obtain workers. The development of ever-more-sophisticated forms of armed conflict provided a major fuel—according to evolutionary anthropologist Paul Bingham (2000), the most important fuel—for the evolution of human knowledge and culture.

The food-related picture of cognitive evolution sketched by Kringelbach suggests that energetic concerns should be important in the development of social behaviour generally, not just in humans. This implicit prediction is dramatically—and unexpectedly—supported by a recent comparative study of ‘worker policing’ of reproduction in a large number of species of Hymenoptera, which includes colonial ants, bees, and wasps (Hammond and Keller 2004).

The study aimed to test the generally accepted hypothesis that relatedness (kin selection) is the critical factor in worker policing, an important mechanism for maintaining social harmony in group-living species by suppressing selfish behaviour by individuals, in this case, reproduction by workers resulting in male offspring. Egg laying by colony members other than the queen is discouraged by non-laying workers, who eat or remove eggs from the nest and behave aggressively toward egg layers. According to the relatedness hypothesis, worker policing should occur only where workers are more closely related to male eggs produced by the colony’s queen than they are to male eggs produced by fellow workers. Comparative analysis of data from 50 species of social Hymenoptera showed that “self-restraint and worker-policing” are indeed “widespread and powerful mechanisms” regulating colonial reproduction (Hammond and Keller 2004, p 0007). Unexpectedly, however, the analysis provided little or no support for relatedness as the general explanation. Instead, the results tended to support the “largely ignored” efficiency hypothesis, namely, that reproduction by individual workers is suppressed because the energetic costs to the colony are too high. Time and effort normally used for foraging and brood rearing on behalf of the colony is spent instead laying eggs and in wasteful dominance and protective interactions.

While kin selection is not an unimportant factor in the development of social behaviour, the study demonstrates that it is inadequate to explain the degree of social harmony or the complexity of reproductive regulation found in these colonies. Energetic efficiency alone is also unlikely to offer a complete explanation of complex social behaviour such as worker policing. However, even researchers who responded with caution

to Hammond and Keller’s findings agree that the study clearly demonstrates that energetic efficiency deserves a much higher priority than it has been accorded heretofore in theorizing about the evolution of sociality and the cognitive capacities that subserve it (Atkinson 2004).

In summary, SOCS approaches assume that the key to describing and explaining cognition as a biological function is its role in the energetic economy of an organism, what Corning and Kline (1998b) call the “thermoeconomics” of living systems. This economy is grounded, first and foremost, in the system’s continued self-maintenance far from thermodynamic equilibrium via the importation of endogenous sources of fuel to carry out metabolic and synthetic tasks, and, ultimately, to reproduce. Cognitive capacities, and their evolutionary history are thus, understood first in terms of securing the energetic needs of an organism and overcoming the difficulties associated with obtaining these resources, which include eluding predators and/or besting competitors.

Felix Goodson’s homeostatic equilibrium theory of cognition, presented in impressive detail in *The Evolution and Function of Cognition* (Goodson 2003), is an excellent example of a SOCS-based framework. It is impossible in a short space to do justice to Goodson’s presentation, which begins with differential behaviour along a single energy dimension and ends with language. However, the thesis at the theory’s heart can be simply summarized: a “cognitive world”—using that phrase in its broadest possible sense—is constituted of “functional translations of energy shifts in the external environment”, which are sensed by an organism within the context of its own internal state of energetic balance (p 79). All behaviour, from bacterial chemotaxis to mathematical theorizing, is fundamentally “equilibrium trending” (p 264), i.e., directed toward attaining a state of internal balance. Equilibrium among the physico-chemical-electrical processes that sustain its organization is thus the default goal state of a living system, against which all interactions are calibrated. Goodson’s theory predicts that the greater the homeostatic disequilibrium, the greater the compensatory behaviour will be. This provides the fourth principle:

*Biogenic principle #4—Normativity: Cognition relates to the (more or less) continuous assessment of system needs relative to prevailing circumstances, the potential for interaction, and whether the current interaction is working or not.*

Evolutionarily speaking, Goodson builds the homeostatic equilibrium theory from the ground up. He begins with a series of four plausible inferences about the conditions of early life, which developed and is sustained within “a context of fluctuating energies” (p 45). The inferences are: (1) that primitive life was able to obtain energy from some source, or it would not have existed at all; (2) that it had the capacity to replicate, the basis of Darwinian selection; (3) that it had the capacity for

movement and thus was “selective, or at least directional”; and (4) that it was “made of vulnerable material,” which could be disrupted or harmed (p 41). Differential behaviour, Goodson suggests, was but one of three main survival techniques available to early life forms, the others being physical protection (armour) and replication, either rapidly or in large numbers (pp 42–23).

It should be noted that another truck-sized hole in the biological back story gapes here. Somehow certain types of self-organizing physical system came to value their own persistence, to the extent that they began to seek out energy resources to preserve their existence. Maynard Smith and Szathmáry (1999) notwithstanding, the origin of exploratory, ‘selfish’ behaviour is perhaps the first truly “major transition” in the evolution of life, the thing that really makes living things different from replicating crystals and self-catalyzing reactions (compare Kauffman 2000, chap. 3). There are no theories, not even good guesses, as to how actively self-preserving behaviour emerged. Goodson’s homeostatic equilibrium theory explains the nature and strength of such behaviour according to a principle of reaction, but his theory assumes (and he is quite explicit about this) a persistence-valuing system.

Unusual among contemporary hypotheses, homeostatic equilibrium theory explicitly aims to explain the function in adaptive behaviour of experience (“the total physio-chemical-electrical event”) and sensation (“the way the knowing processes of our body transform the external world so that we both have knowledge of it and can respond appropriately to it”) (Goodson 2003, pp 85). Although this lies squarely in ‘hard problem’ territory, Goodson, significantly, does not talk about consciousness. Rather, following Wundt, he begins with *the field of awareness*, “an area, central point, functional integrator—call it what you will—in which the information pertinent to the operation of the mechanism in question is represented so that effective action can take place” (p 80). Information, on this account, is similar to the classic “difference that makes a difference” (Bateson 1979); it is an energy shift transformed by the organism such that it functions to triangulate the system’s position relative to an environment and thereby to initiate an appropriate response. Systems that transform energy shifts along more than one dimension, and this includes all known organisms existing today, require the capacity to retain information for a length of time greater than zero. This is the fifth biogenic principle.

*Biogenic principle #5—Memory: Cognition requires the capacity to retain information for a length of time greater than zero.*

Take, for example, the ‘swimming’ behaviour of *E. coli* toward a food source. The cell is powered by a flagellum, the rotation of which is modulated by information about environmental conditions detected by receptors embedded in the cell membrane. This

deceptively simple coupling of perception and action depends upon memory (Macnab and Koshland 1972; Adler and Tso 1974; Koshland 1980). Information must be retained, however briefly, to mobilize the appropriate response. Even the simplest gradient sampling has a temporal dimension. Property detections are disjunctive, not continuous; they are intrinsically comparative. For a comparison to be instrumentally useful, there has to be something—some detected property, some content—to be compared (Koshland 1980). For a comparison to occur at all, there has to be some benchmark against which the new information is calibrated. That requires recall, however transient, of what has gone before, even just immediately before. A bacterium may not remember much for long, but it must remember, if only for a few seconds—which may be, relatively speaking, a long time for a microbe. In fact, bacterial behaviour is vastly more complex, flexible and adaptive (not merely adapted) than is generally appreciated, but a detailed exposition is not possible or necessary here (see Lyon 2005, chap. 5). Suffice to say that an individual bacterium’s decision to follow a nutrient gradient depends on the integration of a number of factors, including the nature and concentration of the attractant, whether the organism is nourished or starved, the relative presence or absence of oxygen, the number of conspecifics present and whether collective behaviours are being initiated, and so on.

Living systems exist in a kaleidoscope of different shifting energies, of which they sense only a limited number. The more complex the organism, the wider the range, but the energy shifts capable of being sensed are always far fewer than those actually occurring. What sort of energy shifts, and patterns of shifts, an organism is capable of sensing depends on its history of selection. This provides the sixth principle.

*Biogenic principle #6—Selectivity: Because an organism is capable of interacting profitably with some, but not all, properties of the environment, cognition involves the differentiation of some states of affairs from other states of affairs.*

It is worth noting that there is nothing especially straightforward about how some things and not others become energy sources for an organism. Lactose is food (something to be sought and ingested) for an *E. coli* but not, under normal conditions, for *Geobacter sulfurreducens*, a mineral-munching strain of bacteria. The Earth’s magnetic field lines are essential environmental cues for a wandering red-spotted newt (Fischer et al. 2001), but not for a wandering human without a compass. Every potential energy source carries its own cost for the organism. While photosynthetic organisms may seem to have ‘beat the system’, getting energy for free as it were, photosynthesis is an incredibly complex process and exposure to ultraviolet light damages DNA, which is necessary for growth and reproduction.

Whatever the organism's sensory capacities, however, information inputs must be distinguishable from one another; they must be capable of being prioritised according to the immediate needs of the organism. Those needs, in turn, cannot carry equal weight. This is where sensation, and the intensity or prepotence of sensation—its tolerability—is important, on Goodson's theory. Pain is more intolerable than thirst, which is more intolerable than hunger. That is because "body trauma is more immediately critical for survival than either fluid or energy requirements" (Goodson 2003, p 91). The qualitative differences of sensation are "simply given" and essentially indescribable. However, they are entirely adaptive. On this reading, the question at the heart of the 'hard problem'—why a physico-chemical-electrical transformation should be accompanied by feeling at all—is misguided. If there were no experience or sensation, there would be no basis for prioritizing informational inputs on the basis of primary or secondary need. While bracketing the contentious issue of sensation, the necessity to prioritise informational inputs and system needs provides the basis for the seventh principle:

*Biogenic principle #7—Valency: Relative to the organism's needs and/or experience different properties of the environment will be invested with different degrees of force or significance, both positive and negative.*

Goodson notes that the nature of the transformation (e.g., gene expression, production of macromolecules etc.) is generally of a very different character from the instigating circumstance (e.g., patterns of electromagnetic radiation, relative molecular motion etc.). How the organism experiences the transformation is different again. In order to understand cognition, Goodson suggests, such transformations are not properly conceived in either analogical or digital terms, both of which imply (to him) a homuncular interpreter, but, rather, in functional terms, as contributing to an ongoing process of attaining homeostatic balance. As Goodson notes (p 90), "Organisms react not to a hot iron, but to pain; not to loss of body fluid, but to thirst; not to hours of deprivation, but to hunger". The experience, in sensation, of the continual transformation of shifting energies constitutes the seedbed of all biological behaviour, including all forms of higher cognition.

From this foundation, Goodson builds a convincing case for the emergence of the capacity for focalization as a way of prioritizing the myriad inputs bombarding the organism at any given moment so that the most appropriate response is initiated relative to the system's current state. Goodson calls this capacity, ordinarily identified with attention, apperception. *Apperception*, according to Goodson, is the "most critical operation" in the development of higher cognitive capacities (p 256), including thinking ("internalized locomotion"), dreaming and imagining. How apperception functions, how

information inputs are prioritized, is shaped in turn by a fusion of "the most basic and recurrent experiences in an individual's life" (p 70), what Goodson calls the *autocept*, which forms the basis of an individual's identity and much of her motivation for volitional behaviour. The account provides a satisfyingly rounded picture of the incremental evolution of layers of complexity in the service of adaptive behaviour: sensory inputs; perceptual structuring; learning and memory; the fusion, speed and variables involved in all-important apperception, mentation, reasoning, meaning, the role of action and the emergence of 'composite action systems; the dynamics of reaction; language; and more.

Importantly, Goodson's aim is to provide law-like principles that govern the continuum of behaviour. Contra Fodor (1986), cognition on this account is just as nomologically bound, and by the same principles, as the overt behaviour of the simplest organism. The more complex the organism's capacity for interaction, the more complex its cognitive processes are likely to be, and the greater its energy needs. Cognition, too, is costly. Although it weighs on average a mere kilogram and a half—one seventy-fifth of the average adult male's body weight—the human brain commands one-fifth of the body's total energy budget. The capacities Goodson regards explicitly as cognitive (e.g., observation learning, "world internalization," differentiated forms of memory) emerge as a coordination solution to a combinatorial explosion of proliferating information inputs as an organism and its relation to a niche become more complex (Goodson 2003, pp 262–264). Thus while Goodson's theory addresses what-it-does in detail, the what-it-is of cognition unfortunately remains imprecise.

In short, the SOCS-based approach to cognition provides at least seven, biologically well-characterized, empirical constraints on theory. However, important blanks remain at the heart of the biological back story that remain to be filled in.<sup>10</sup> Unfortunately, the zones of *terra incognita* in the biological story often lie precisely at the point where explanations of animate organization and explanations of behaviour and cognition intersect.

<sup>10</sup>Another gap relates to organisms' "limited autonomy from local energy potentials" and their ability to "vary their rate of energy consumption independently of variations in local gradients" (Barham 1996). This is possible because organisms have their own on-board energy supply in the form of adenosine triphosphate (ATP). It is a biological system's "ability to use low-energy fluxes from a distal source in order to detect high-energy potentials before it becomes thermodynamically coupled with them" that is the odd trick, according to Barham (p 239). This capacity is contingent upon the system's ability to "distinguish between those conditions external to itself that will support its continued oscillation, and those which will not" (p 238). Under starvation conditions, for example, certain species of bacteria will sporulate, a process that induces dramatic, global changes in cell state such that the organism can hunker down indefinitely until conditions improve (Marahiel and Zuber 1999). Sporulation is highly energy intensive and, in some cases, irreversible to the extent that the bacterium cannot 'change its mind' halfway through the process. The sporulation option, therefore, involves a calculated risk regarding the extent to which conditions will support "continued oscillation".

The theory of cognition advanced by the Chilean neurobiologists Humberto Maturana and Francisco Varela (1980) is inseparable from the theory of animate organization they call autopoiesis, which addresses some of the shortcomings of the SOCS approach descriptively even as it fails to explain them. I have argued elsewhere that the autopoietic theory of cognition was the first truly biogenic approach to cognition since Aristotle (Lyon 2004). The key insight of autopoiesis is that biological organization is self-producing, not merely self-organizing. Organisms are continually produced by a network of components, which are themselves being continually produced by networks of components. This continuous cycle of self-synthesis, by networks within networks that both produce work and produce themselves, is what biological systems are, no more, no less. For a Boeing 747 to be autopoietic, it would have to be capable of synthesizing the machinery that manufactures the vast array of components that make up the aircraft, and simultaneously produce those components, while in flight. This emphasis on continual self-production and its maintenance is what distinguishes autopoiesis from SOCS approaches to life and cognition.

Although weaker versions have been developed since (Beer 1990; Varela et al. 1991), the original autopoietic theory of cognition is as strong as a biogenic approach gets. It can be stated thus: cognition is the domain of interactions of a system with its surrounding medium by which the system maintains autopoiesis. As Maturana puts it in *The Biology of Cognition* (1970/1980): “Living systems are cognitive systems, and living as a process is a process of cognition” (p 13). John Stewart (1996) abbreviates the view as “life = cognition”. The equation is saved from being a meaningless tautology by the detailed account of how and why the equation holds and its implications for more complex elaborations of cognition, including language.<sup>12</sup> The theory of evolution by natural selection has been criticized for being similarly tautological (Richards 1987): the fittest are fit because they survive, and they survive because they are fit. Nevertheless, natural selection is the most successful theory in biology because it makes sense of a wide variety of biological phenomena. We have nothing even remotely comparable for making sense of cognition (Rose 1998; Silver 1998; de Waal 2002), so the appear-

ance of circularity is a poor reason for dismissing a theory that, while not unproblematic, has demonstrable virtues.

The autopoietic model of cognition rests on four principles: (1) interaction necessitated by circular causation; (2) operational closure, which supports autonomy and self-reference; (3) structural determinism; and (4) structural coupling.

A system that is self-maintaining far from thermodynamic equilibrium necessarily involves patterns of change whose causal flow is intrinsically circular. This is especially true of homeostasis. Genes are transcribed and translated to produce macromolecules that induce changes (or cascades of changes) that induce further gene expression. Autopoietic theory recognizes that *circular causation* is the key to every aspect of living organization, necessitating an organism’s continual interaction with its surrounding medium.<sup>13</sup> If a living system ceases to interact with its surrounding medium, it dies; it can no longer produce the components that sustain its organization. If it interacts inadequately with its surrounding medium, it also it dies. Everything an organism does is aimed at maintaining the particular sort of autopoietic organization that makes it a member of the class it is. Different phyla, genera and species maintain autopoiesis in different ways, but they all maintain autopoiesis. Autopoietic organization thus determines the types of interaction of which the system is capable. Organization on this picture does not equate with structure. A system’s material structure continually changes; its organization does not and cannot. Autopoietic organization is what sustains the system’s vitality; if it ceases, the system is no more.

As already noted, the medium with which an organism interacts is heterogeneous and contains many more elements that affect system maintenance. Interactions adequate to survival and reproduction, therefore, require the capacity to differentiate relevant from irrelevant states. A living system’s “domain of interactions”—the sphere in which a system responds differentially to maintain autopoiesis—is, therefore, the “domain of cognition” (Maturana 1970/1980). In his early work, Maturana suggested that the domain of interaction was cognitive for another reason, because it involved an implicit prediction that certain classes of interaction would occur again. Although Maturana later resiled from this position, on the basis that organisms actually interact in a continuous present, I believe his original view captures something important about the nature of cognition and the temporal directedness of biological systems more generally, which other thinkers have developed in detail elsewhere (Rosen 1985). This provides the eighth principle:

<sup>11</sup>This section is a summary of a longer, more detailed presentation in Lyon (2004). Please note that Maturana has consistently declined to characterize as a ‘theory’ the framework he developed in partnership with Varela and others, and indeed it has been criticized for not being a proper theory (see especially Scheper and Scheper 1996). But as autopoiesis constitutes a coherent conceptual structure that provides explanations and makes predictions, ‘theory’ is an appropriate label, in my view.

<sup>12</sup>It is beyond the scope of this paper to show how autopoietic theory accounts for complex cognitive phenomena such as language use. Suffice to say that the theory recently has proven as influential in disciplines related to education, business systems, management and nursing as it has in relation to cognition.

<sup>13</sup>Maturana and Varela in their early work resiled from using the word ‘environment’ on the basis that it was observer-dependent and encompassed a broader view than which the system itself was capable. The observer/system distinction is critical to the autopoietic model.

*Biogenic principle #8—Anticipation: Cognition is intrinsically future-oriented (what happens next?) and thus is predictive.*

Because all biological organisms have a domain of interaction due to their circular organization, on the autopoietic account it is a mistake to equate cognition with possession of a nervous system. A nervous system does not create cognition but, rather, expands an organism's sphere of possible interactions. For every living system, possessing a nervous system or not, cognition consists of the generation of behaviour in a domain of interaction.

While SOCS approaches emphasize thermodynamic openness, autopoiesis emphasizes closure, but of a particular sort. Although a living system is open to matter and energy, it is not open to every form of matter and energy. What can or cannot pass through an organism is determined by the boundary of its organization, which also determines the outer limit of its processes of self-production. No organism exists, therefore, without *operational closure*. Operational closure makes a living system autonomous, which, minimally, is the capacity to robustly sustain processes relevant to system maintenance despite changes in the surrounding medium. Autopoiesis—indeed, homeostasis of any kind—is impossible without operational closure (see also Rosen 2000, p 184). The total symphony of response serves to support the system's robustness, a key characteristic of all biological systems (Kitano 2002). This aspect of living systems provides the ninth biogenic principle:

*Biogenic principle #9—Randomness reduction: Cognition is an important mechanism by which biological systems reduce and modulate the influence of random perturbations on their functioning and are, thereby, robust to perturbation.*

Operational closure, boundedness, influences an organism's cognitive domain primarily in two ways. First, it provides the reference point for 'self' and the distinction of 'non-self', which also form the basis of affective response (see also Damasio 1999). All components within the system boundary that interact to maintain autopoiesis constitute 'self'. The manner in which a system differentiates self may be mimicked, as by some parasites, or masked, as in the case of endogenous retroviruses that trigger an autoimmune response. Some living systems may also regard some or all of the products of their activity as 'self'. But the reference point for such attributions, as well as mimicking and masking, is the operational closure of the affected or the attributing system. Second, because operational closure is the requisite condition for autopoiesis it defines the organism's domain of interactions. The sort of objects and events an organism is capable of encountering depends on its structure, including its

sensory capacities; but the capacity for sense perception itself depends upon the sort of living system it is, which in turn is determined by operational closure.

Organisms cannot enter into interactions that are not specified by their organization, which in turn specifies the processes necessary for continued autopoiesis. However, it is the organism's structure, i.e., the molecular and macro-molecular components that constitute its class-specific organization, which actually implements interactions. Thus, autopoiesis occurs and is maintained at the molecular level, where every interaction effects an immediate change in the system (Maturana and Varela 1973/1980). This feature, which organisms share with inanimate systems capable of interaction, is structural determinism (Maturana and Varela 1992, p 96).<sup>14</sup>

*Structural determinism* implies nothing at all about the predictability of the system's behaviour, however. Autopoiesis is not deterministic in a clockwork sense. What structural determinism suggests is that "every perturbation, every experience, every internal event changes the structure of the network that constitutes the organism" and thus influences, strongly or weakly, its interactions (von Glasersfeld 1997, para 25). Each response to perturbation can form new pathways for interaction or activate and reinforce existing ones. The weight each change carries within the economy of the system varies from moment to moment, and an incomprehensible multitude of changes are occurring at every instant. Structural determinism runs in two directions, from the bottom up and from the top down. The effects of molecular interactions ramify and amplify into behaviour at the macro-molecular level, up to the organism level. Likewise, how an organism behaves ramifies to its internal molecular dynamics.

A central claim of autopoietic theory, unusual given the behaviourism dominant at the time it was advanced, is that the effect of an interaction on an organism is not determined by a stimulus external to the organism. All an external stimulus can do is trigger a structural change within the organism. Only the organism's aggregate state at a given moment can determine what happens next.<sup>15</sup> Herein lies the implication of structural determinism for cognition, in the adequacy or inadequacy of an interaction, or behaviour. Here also the difference between the perspective of an observer of an organism and the perspective of the organism itself provides divergent criteria of adequacy. From the perspective of an observer the assessment of adequacy depends on the

<sup>14</sup>Robert Rosen came to a similar conclusion regarding 'state determinism' in his biological rendering of dynamical systems theory. "In a nutshell, a system which is both (thermodynamically) open and autonomous...must have the property that the flows from environment to system, and from system to environment, are determined by what is inside the system" (Rosen 2000).

<sup>15</sup>I have niggling doubts about this claim. If a shark eats a fish, autopoiesis will cease and the fish will die. Granted, the cessation of autopoiesis is the immediate cause of death, but surely the shark is more than a mere 'trigger' for change.

interests of the observer in making the observation of the interaction, which in turn is shaped by the conceptual framework from which the observation is made. The criterion of adequacy thus will differ, sometimes subtly, sometimes greatly, from observer to observer. This, in my view, provides a plausible explanation for the huge differences among investigators in their ascriptions of cognition. Adequacy from the perspective of the interacting system, on the other hand, is more straightforward and pragmatic, on this account. Does the interaction work? Given this interaction, are autopoiesis and adaptation conserved?

On the autopoietic model knowledge is an ascription made by an observer when a behaviour meets some standard of adequacy, a standard that may be independent of the observed system (Maturana 2003, pp 26–67). However, for a behaving system to know is to interact in a manner that is both familiar to the system, usually the result of a repetition of a previous interaction, and adequate to maintain autopoiesis and adaptation. The domain of knowing, the cognitive domain, is thus the domain of adequate action, and it changes continually as the structure of the system and the structure of the surrounding medium continually change.

The principle of structural determinism generates problems for the autopoietic approach to cognition, notably in its implications for agency. In his later work, Maturana describes a system's interaction with its niche, as well as its development during its lifetime, as "a process without alternatives" (Maturana 1990, p 76). This seems to imply that the way things are is the only way they could ever have been, an implication at once trivial and fatalistic. The "process without alternatives" view suggests that, at least in the autopoietic model as originally proposed, there is no such thing as agency. No alternatives mean no "decision points" (Maturana 1990, p 87). No decision points mean no purposes or goals. No goal orientation means no agency. Maturana seems concerned that to concede agency, or teleonomic developmental processes, is to concede the presence of "a general organizational principle or force guiding the operation of the molecules that compose (the system)," over and above the local interactions of those molecules (Maturana 2003, p 17). I see no such implication. Global as well as local constraints shape a system. After all, the possible interactions of structural components are specified by the system's organization as an integrated, operationally closed whole. Agency, minimally, is the ability to engage in action to further system-determined goals, and there is nothing in structural determinism to prevent a system having goals, even explicit ones. Existence conditions, such as the maintenance of continued autopoiesis, are, arguably, implicit goals for the system, not merely something imputed by an observer. Continued autopoiesis is the end toward which interaction is directed, and I see no reason why there could not be hierarchies of ends subserving the overarching one.

Finally, an autopoietic system does not and cannot exist apart from its surrounding medium, or its niche.

The niche is defined by the interactions into which an organism may enter and thus constitutes the organism's 'cognitive reality.' Trivially, a niche also cannot be understood separately from the system whose interactions with it bring the niche into existence by definition. *Structural coupling* denotes the interdependence of organism and niche such that a change in one brings about a change in the other (Maturana and Varela 1973/1980; Maturana 2003). Structural coupling is the conjoint result of thermodynamic openness, which allows the flow of matter and energy through the organism, and operational closure, which enables autopoiesis and homeostasis. As the interface of interaction between organism and niche, the domain of structural coupling defines the organism's cognitive domain. For this reason, the model could just as easily be called the 'structural coupling theory of cognition' as it could be the 'autopoietic theory of cognition'.

The adaptation of organism to niche is described on this account in terms of operational coherence. In contrast to the traditional view, adaptation is not "a variable in the evolutionary discourse" but, rather, "an invariant relation that constitutes a condition of existence for living systems" (Maturana 2003, p 17). A living system that maintains autopoiesis is adapted to its niche because its operations cohere with—they are not contradicted or thwarted by—the surrounding medium. If the organism were maladapted in this sense, it could not survive. An organism's interactions may be more or less 'optimal' according to some criterion, but optimality, on this account, is strictly an observer-dependent distinction. Adaptation, therefore, is an intrinsically cognitive phenomenon because it is determined by the adequacy of the organism's interaction with its niche.

*Knowing* is defined broadly as "effective action," that is, "an action that will enable a living being to continue its existence in a definite environment" (Maturana and Varela 1992, p 29). Maturana extracts from this principle the claim that "a living system is *necessarily* always engaged in adequate action" so long as autopoiesis is maintained (Maturana 1990, p 89, my italics).

I am uncertain what this statement means, but surely it is not that organisms never make mistakes, or that an error that fails to kill the system (cause autopoiesis to cease) is just another sort of interaction on par with all other interactions. If this were the case, it would imply that biological systems have no norms of effective operation from the system's perspective relative to different pathways of interaction. Clearly, this is not the case. An animal can be sick, a plant diseased; an interaction may cause pain or damage but not death. A system's interaction with its medium may so alter the medium that the system's continued existence is threatened. How can potentially catastrophic anthropogenic climate change be anything but a mistake—from both the perspectives of the observer and of the (human) living systems whose interactions are bringing it about. Existential parameters may vary across a range, but presumably homeostatic regulation tends toward

balance that is optimal from the system's standpoint. It is unclear how to account for internal processes of control and their evolution if there are no norms. But norms are relative—to implicit goals, at the very least the implicit goal of continued autopoiesis.

By the same token, to describe cognition as a 'function', according to the autopoietic model, is to draw a distinction that is not intrinsic to the system. In the classic formulation, the map is not the territory. From the system's perspective, cognition can no more be demarcated from respiration, digestion, circulation, and elimination than these processes can be differentiated from any other fundamental process that sustains autopoiesis. At the molecular level, where autopoiesis takes place, processes are concatenations that ramify and loop back; they dynamically overlap, interweave and interact. What an observer designates as an organism's 'cognitive subsystems' will always have substantially linked, if not shared, molecular pathways with other systems usually considered to be non-cognitive—just as the brain, so often equated with mind, supports 'physical' functions as well as 'mental' ones, and it is difficult to determine where one sort ends and the other sort begins. This provides us with the final biogenic principle:

*Biogenic principle #10—Interdependence: The biochemical pathways subserving cognition are intimately linked to those of other biological functions, making delineation difficult and largely a function of explanatory goals. (The map is not the territory.)*

Similarly, homeostatic equilibrium theory predicts that cognitive capacities normally parsed as separate—for example, sensation, perception, attention, motivation, affect, learning, memory, and so on—will prove to be “all dynamically and perpetually interdependent” not only with each other but also with other physiological processes that maintain balance within the

organism (Goodson 2003, p 56). They do not just “shade off” into one another, as Godfrey-Smith (2003) puts it; they function interdependently. Despite the obvious value of lesion studies, there is ample empirical evidence to bear this out.

Although their emphases are different, SOCS and autopoietic approaches are clearly resonant in important ways. The explanations of cognition that, to my knowledge, fall under the two biogenic approaches sketched here are listed in Table 1.

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## Discussion

Table 2 summarizes the traits of the anthropogenic and biogenic families of cognitive explanation for comparison. Clearly, neither the number of principles, nor their empirical or theoretical solidity, is comparable. Not only are there more traits constraining biogenic theorizing, the principles also rest on firmer theoretical foundations. The key concepts enjoy a high degree of interdisciplinary agreement, enabling meaningful comparison of results between studies and experiments with different aims. As the knowledge base of the life sciences develops and grows, conceivably the list of biogenic principles will grow, too. With anthropogenic theoretical approaches, on the other hand, incommensurability between frameworks is not uncommon, the meaning of key terms require elaboration more or less on a case-by-case basis, and it is hard to see from what source new principles could emerge. By comparison to the biogenic approach, the anthropogenic ground is well trodden indeed.

Needless to say, there is nothing to prevent an investigator taking an anthropogenic approach to a particular cognitive issue—in, say, an experiment involving self report of episodic memory—from taking biogenic family traits on board to good effect. Likewise, there is no reason that a species of biogenic explanation could not incorporate some or all of the anthropogenic

**Table 1** Species of biogenic explanation

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<b>SELF-ORGANIZING COMPLEX SYSTEMS</b>
Genetic epistemology (Piaget 1970)
Evolutionary epistemology (Popper 1965/1972; Campbell 1974)
Ecological approach to perception (Gibson 1979)
Interactivism (Bickhard 1980; Bickhard and Terveen 1995)
Anticipatory systems model (Rosen 1985)
Intelligence without representation (robotics) (Brooks 1991)
Embodied information model (Barham 1996)
Somatic marker hypothesis (Damasio 1999)
Self-directed autonomy model (Christensen and Hooker 2000; Christensen 2004)
Intelligent network model (Vertosick 2002)
Evolutionary energetic (EN) model (La Cerra and Bingham 2002)
Homeostatic equilibrium theory (Goodson 2003)
<b>AUTOPOIESIS</b>
Autopoietic theory of cognition (Maturana 1970/1980; Maturana and Varela 1973/1980)
Enactivism (Varela, Thompson et al. 1991)
Adaptive intelligence (Beer 1990)
Autopoietic immunity model (Stewart and Coutinho 2004)
<b>SYNTHETIC APPROACHES</b>
Behavioural systems theory (Keijzer 2001)

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**Table 2** Anthropogenic & biogenic family traits

ANTHROPOGENIC	BIOGENIC
1. <i>Brain</i> : Cognition is implemented or instantiated in the brain and/or nervous system.	1. <i>Continuity</i> : Complex cognitive capacities have evolved from simpler forms of cognition. There is a continuous line of meaningful descent. (Does not rule out the emergence of novel capacities with increasing complexity).
2. <i>Behaviour</i> : Cognition has an important role in generating adaptive behaviour.	2. <i>Control</i> : Cognition directly or indirectly modulates the physico-chemical processes that constitute an organism.
3. <i>Information processing</i> : Cognition involves the computational transformation of information inputs, from within the system or from the environment, leading to an output that is behaviourally overt or covert, that is, internal to the system.	3. <i>Interaction</i> : Cognition facilitates the establishment of reciprocal causal relations with features of the environment, leading to exchanges of matter and energy that are essential to the organism's continued persistence, well being or reproduction.
4. <i>Complex traits</i> : An adequate theory of cognition must account for complex behavioural traits such as language, abstract thinking, beliefs and desires, phenomenal consciousness, and culture.	4. <i>Normativity</i> : Cognition relates to the (more or less) continuous assessment of system needs relative to prevailing circumstances, the potential for interaction, and whether the current interaction is working or not.
5. <i>Intentionality</i> : A distinguishing property of cognition is that it is directed toward (or about) some state of affairs in the world.	5. <i>Memory</i> : Cognition requires the capacity to retain information for a length of time greater than zero.
6. <i>Representation</i> : Because it is directed toward a state of affairs, a cognitive state has a representational content.	6. <i>Selectivity</i> : Because an organism is capable of interacting profitably with some, but not all, properties of the environment, cognition involves the differentiation of some states of affairs from other states of affairs.
	7. <i>Valency</i> : Relative to the organism's needs and/or experience different properties of the environment will be invested with different degrees of force or significance, both positive and negative.
	8. <i>Anticipation</i> : Cognition is intrinsically future-oriented (what happens next?) and thus predictive.
	9. <i>Randomness reduction</i> : Cognition is an important mechanism by which biological systems reduce and modulate the influence of random perturbations on their functioning and are, thereby, robust to perturbation.
	10. <i>Interdependence</i> : The biochemical pathways subserving cognition are intimately linked to those of other biological functions, making delineation difficult and largely a function of explanatory goals. (The map is not the territory.)

family traits. Goodson's theory, which draws on information processing and representationalist principles, is a case in point.

It is important to stress that the two approaches are not mutually exclusive; indeed, both are necessary for a complete picture. We must understand what cognition is and what it does as a natural phenomenon, but we also have to understand human psychological experience. It is a matter of horses for courses, and productive borrowing is optional. The traits outlined here are what currently is required of an explanation in the particular family, whether anthropogenic or biogenic. Because cognition is naturally a biological function, the empirical strength and relative conceptual clarity of its principles would seem to make the biogenic approach the logical choice for attempting a general theory of cognition that generates testable empirical generalizations.

Biogenic approaches also appear to stand a better chance of avoiding some long-standing philosophical problems, such as those relating to mental causation and the ontological status of normativity, possibly even the 'hard problem' of consciousness. Of course, serious philosophical issues remain relating to the status of emergent phenomena more generally—including, but not limited to, macroscopic physical phenomena such as

tables and chairs, whose characteristics and 'causal powers' are irreducible to particle physics no matter what defenders of physicalism might claim—but the issue at least becomes much more general and not a peculiar worry of the mind–body relation.

Despite their shortcomings biogenic approaches have the virtue of throwing light on important aspects of the biology of cognition. The SOCS approach stresses the role of cognition in maintaining the energetic balance of the organism and the intrinsic normativity of homeostasis. Autopoiesis emphasizes the self-referential nature of biological organization and the inseparability of organism and niche, despite the self-determined nature of an organism's interaction with its surrounding medium. Biosemiotics, although still diffuse, highlights the fundamental importance of selectivity, or meaning, at every level of living organization. Synthetic approaches show promise as a means of incorporating the strengths and avoiding the weaknesses of the main branches of the biogenic family. For example, Keijzer's behavioural systems theory, which incorporates elements of SOCS and autopoiesis, clearly demonstrates that so-called 'basic behaviour' poses an explanatory challenge potentially every bit as daunting as putatively 'genuine' cognition (Keijzer 2001). There are also real gaps in the

underlying biological story, but these gaps are effectively invisible to anthropogenic approaches.

Because they are species non-specific, biogenic approaches are capable of incorporating more smoothly behavioural data from diverse sources in a wider range of disciplines. Because they are grounded in primary existential goals, biogenic approaches also have good reason to presume, without the need for abstract conceptual argument, that cognition is intrinsically active, pragmatic, motivated and constructive. In other words, perception is structured not only by the sensory mechanisms of an organism but also by species-specific and individually conditioned capacities for normative assessment. As Walter Freeman's research with olfaction in rabbits has shown, no two exposures to the same stimuli elicit the same pattern of neural response (Freeman 1999). A biogenic approach such as homeostatic equilibrium theory suggests why this is so: the organism is an aggregation of a multitude of dynamic processes constantly in flux, and part of what is changing is the organism's relationship not only to an environment but also to itself.

Significantly, what the biogenic approach seems to suggest is that agency, the capacity to adaptively change (act, interact) relative to an environment, and normative assessment, the capacity to opt to do this rather than that in the present circumstances, given present needs, are the dual bases of cognition, and possibly the foundation of all of the processes the anthropogenic tradition tells us pertain to mind. To enable successful action and interaction within a niche is arguably what cognition is for. The capacity to infer relations between external circumstance and internal need to facilitate agency may be, to a first approximation, what cognition is. In my view, this is the direction in which a general theory lies.

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## References

- Adler J, Tso W-W (1974) 'Decision'-making in bacteria: chemotactic response of *Escherichia coli* to conflicting stimuli. *Science* 184(4143):1292–2294
- Anolli L, Riva G et al (eds) (2005) The hidden structure of interaction: from neurons to culture patterns. Emerging communication: studies on new technologies and practices in communication. IOS Press, Amsterdam
- Atkinson N (2004) Insect policing carries costs. *The Scientist*, BioMed Central
- Bak P (1996) How nature works: the science of self-organized criticality. Copernicus/Springer, New York
- Balazs A (2004) What does a molecule want? The myth of the self-replicating molecule (comments on the "selfish-gene" paradigm). *Biosystems* 73(1):1–11
- Barham J (1996) A dynamical model of the meaning of information. *Biosystems* 38(2–2):235–541
- Bateson G (1979) Mind and nature: a necessary unity. E.P. Dutton, New York
- Bechtel W (1998) Representations and cognitive explanations: assessing the dynamicist's challenge in cognitive science. *Cogn Sci* 22(3):295–517
- Bechtel W, Abrahamsen A (1990) Beyond the exclusively propositional era. *Synthese* 82(2):223–353
- Bechtel W, Abrahamsen A et al. (1998) The life of cognitive science. In: Bechtel W, Graham G (eds) A companion to cognitive science. Blackwell, Malden, pp 1–104
- Beer RD (1990) Intelligence as adaptive behavior: an experiment in computational neuroethology. Academic, San Diego
- Bickhard MH (1980) Cognition, convention, and communication. Praeger Publishers, New York
- Bickhard MH (1998) Levels of representationality. *J Exp Theor Artif Intell* 10(1998):179–915
- Bickhard MH, Terveen L (1995) Foundational issues in artificial intelligence and cognitive science: impasse and solution. Elsevier, Amsterdam
- Bingham PM (2000) Human evolution and human history: a complete theory. *Evol Anthropol: Issue News Rev* 9(6): 248–857
- Boden MA (ed) (1996). The philosophy of artificial life. Oxford Readings in Philosophy. Oxford University Press, Oxford
- Brier S (2000) Biosemiotics as a possible bridge between embodiment in cognitive semantics and the motivation concept of animal cognition in ethology. *Cybernet Human Know* 7(1): 57–75
- Brooks R (1991) Intelligence without representation. *Artif Intell* 47(1–1):139–959
- Byrne RW, Barnard PJ et al. (2004) Understanding culture across species. *Trends C Sc* 8(8):341–146
- Cairns-Smith AG (1985) Seven clues to the origin of life. Cambridge University Press/Canto, Cambridge
- Campbell DT (1974) Evolutionary epistemology. In: Schlipp PA (ed) The philosophy of Karl Popper. Open Court, La Salle, Ill., 1:413–363
- Chalmers DJ (1996) The conscious mind. In search of a fundamental theory. Oxford University Press, New York
- Cherniak C (1986) Minimal rationality. MIT Press/Bradford, Cambridge
- Chomsky N (1981) The case against B.F. Skinner. In: Bolles EB (ed) Galileo's commandment. Abacus (Little, Brown and Company), London, pp 80–107
- Christensen WD (2004) Self-directedness: a process approach to cognition. *Axiomathes* 14:171–189
- Christensen WD, Hooker CA (2000) Autonomy and the emergence of intelligence: organized interactive construction. *Commun Cogn Artif Intell* 17(3/4):133–357
- Churchland PS (1987) Epistemology in the age of neuroscience. *J Philos* 84:544–455
- Churchland PM (1989) A neurocomputational perspective: the nature of mind and the structure of science. MIT Press, Cambridge
- Clapin H, Staines P et al (eds) (2004) Representation in mind: new approaches to mental representation. Perspectives on cognitive science. Elsevier, New York
- Clark A (1997a) Being there: putting brain, body and world back together again. MIT Press/Bradford, Cambridge, MA
- Clark A (1997b) The dynamical challenge. *Cogn Sci* 21(4):461–181
- Cliff D, Noble J (1997) Knowledge-based vision and simple visual machines. *Philos Trans: Biol Sci (R Soc Lond)* 352:1165–5175
- Copeland BJ (1996) What is computation? *Synthese* 108(3): 335–559
- Corning PA, Kline SJ (1998a) Thermodynamics, information and life revisited, Part I: 'To be or entropy'. *Syst Res Be* 15(4): 273–395
- Corning PA, Kline SJ (1998b) Thermodynamics, information and life revisited, Part II: Thermoeconomics and Control information. *Syst Res Be* 15(6):453–382
- Crane T (1998) Intentionality as the mark of the mental. In: O'Hear A (ed) Current issues in philosophy of mind. Cambridge University Press, Cambridge, pp 229–951

- Crist E (2002) The inner life of earthworms: Darwin's argument and its implications. In: Bekoff M, Allen C, Burghardt G (eds) *The cognitive animal: empirical and theoretical perspectives on animal cognition*. MIT/Bradford Book, Cambridge, p 3
- Damasio AR (1999) *The feeling of what happens, body and emotion in the making of consciousness*. Harcourt Brace & Company, New York
- Darwin C (1874/1909) *The descent of man. Selection in relation to sex*. John Murray, London
- de Waal FBM (2001) *The ape and the sushi master. Cultural reflections by a primatologist*, Allen Lane. The Penguin Press, London
- de Waal FBM (2002) Evolutionary psychology: the wheat from the chaff. *Curr Directions Psychol Sci* 11(6):187–791
- Deacon TW (1997) *The symbolic species: the co-evolution of language and the brain*. W. W. Norton & Company, New York
- Dennett DC (1989) *Cognitive ethology: hunting for bargains or a wild goose chase?* In: Montefiore A, Noble D (ed) *Goals, no-goals and own goals. A debate on goal-directed and intentional behavior*. Unwin Hyman, London, pp 101–116
- Dennett DC (1991) *Consciousness explained*. Penguin Books, London
- Dennett DC (1996) *Kinds of minds. Towards an understanding of consciousness*. Weidenfeld & Nicolson, London
- di Primio F, Müller BS et al. (2000) Minimal cognition in unicellular organisms. In: SAB 2000, sixth international conference on the simulation of adaptive behaviour, Paris, International Society for Adaptive Behaviour
- Dretske F (1988) *Explaining behavior*. MIT Press, Cambridge
- Dretske F (2000) *Perception, knowledge and belief: selected essays*. Cambridge University press, Cambridge
- Dupuy J-P (2000) *The mechanization of the mind: on the origins of cognitive science*. Princeton University Press, Princeton
- Eder J, Rembold H (1992) *Biosemiotics—a paradigm of biology*. *Naturwissenschaften* 79:60–107
- Eigen M, Schuster P (1979) *The hypercycle: a principle of natural self-organization*. Springer, New York
- Emmeche C (1998) Defining life as a semiotic phenomenon. *Cybernet Human Know* 5(1):3–37
- Fischer JH, Freake MJ et al (2001) Evidence for the use of magnetic map information by an amphibian. *Anim Behav* 62(1):1–10
- Fodor JA (1986) Why paramecia don't have mental representations. *Midwest Stud Philos X*:3–33
- Freeman WJ (1999) *How brains make up their minds*. Phoenix Paperback, London
- Gardner H (1985) *The mind's new science: a history of the cognitive revolution*. Basic Books, Inc., Publishers, New York
- Gibson JJ (1979) *The ecological approach to visual perception*. Houghton Mifflin, Dallas
- Godfrey-Smith P (1996) *Complexity and the function of mind in nature*. Cambridge University Press, Cambridge
- Godfrey-Smith P (2003) Between Baldwin skepticism and Baldwin boosterism. In: Weber BH, Depew DJ (eds) *Evolution and learning: the Baldwin effect reconsidered*. MIT Press/Bradford, Cambridge, pp 53–37
- Goodson FE (2003) *The evolution and function of cognition*. Lawrence Erlbaum Associates Inc., Mahwah, NJ
- Gray RD (1994) Sparrows, matching and the ideal free distribution - Can biological and psychological approaches be synthesized. *Anim Behav* 48(2):411–123
- Hammond RL, Keller L (2004) Conflict over male parentage in social insects. *PLoS Biol* 2(9):e248
- Hardcastle VG (2001) *Consciousness: chili of the brain*. *Conscious C* 10:418–820
- Harnad S (1993) Problems, problems: the frame problem as a symptom of the symbol grounding problem. *Psychology* 4(34):(11)
- Haselager P, de Groot A et al. (2003) Representationalism vs. anti-representationalism: a debate for the sake of appearance. *Philos* 16(1):5–53
- Haugeland J (1997) What is mind design? In: Haugeland J (ed) *Mind design II: philosophy, psychology, artificial intelligence*. MIT/Bradford, Cambridge, pp 1–18
- Hoffmeyer J, Emmeche C (1991) Code-duality and the semiotics of nature. In: Anderson M, Merrell F (ed) *On semiotic modeling*. Mouton de Gruyter, Berlin, pp 117–766
- Holmes B (2004) Manna or millstone. *New Sci* 183(2465):29–91
- Hull DL (2001) That just don't sound right: a plea for real examples. In: Hull DL (ed) *Science and selection: essays on biological evolution and the philosophy of science*. Cambridge University Press, Cambridge, pp 196–621
- Hurley SL (1998) *Consciousness in action*. Harvard University Press, Cambridge
- Husserl E (1952) *Ideas: general introduction to a pure phenomenology*. Allen & Unwin, London
- Jennings HS (1905/1962) *Behavior of the lower organisms*. Indiana University Press, Bloomington
- Kauffman S (2000) *Investigations*. Oxford University Press, Oxford
- Keijzer F (2001) *Representation and behavior*. MIT Press/Bradford Book, Cambridge
- Kerepesi A, Jonsson GK et al (2005) Detection of temporal patterns in dog-human interaction. *Behav Proc* 70(1):69–99
- Kitano H (2002) *Systems biology: a brief overview*. *Science* 295(1 March 2002):1662–2664
- Koshland DE Jr (1980) *Bacterial chemotaxis as a model behavioral system*. Raven Press, New York
- Kringelbach ML (2004) Food for thought: hedonic experience beyond homeostasis in the human brain. *Neuroscience* 126(4):807–719
- La Cerra P, Bingham R (2002) *The origin of minds*. Harmony Books, New York
- Lawton G (2004) *Urban legends*. *New Sci* 183(2465):32–25
- Levi-Strauss C (1969) *The raw and the cooked*. Harper & Row, New York
- Lockery S (1989) Representation, functionalism, and simple living systems. In: Montefiore A, Noble D (eds) *Goals, no-goals and own goals. A debate on goal-directed and intentional behaviour*. Unwin Hyman, London, pp 117–758
- Lyon P (2004) *Autopoiesis and knowing: reflections on Maturana's biogenic explanation of cognition*. *Cybernet Human Know* 11(4):21–16
- Lyon P (2005) *Agent in the organism: toward a biogenic theory of cognition*. PhD thesis, Australian National University (forthcoming)
- Macnab RM, Koshland DE (1972) The gradient-sensing mechanism in bacterial chemotaxis. *PNAS* 69(9):2509–9512
- Macphail EM, Bolhuis JJ (2001) The evolution of intelligence: adaptive specialization versus general process. *Biol Rev Camb Philos Soc* 76(3):341–164
- Marahiel MA, Zuber P (1999) Sporulation and cell differentiation. In: Lengeler JW, Drews G, Schlegel HG (eds) *Biology of the prokaryotes*. Blackwell, New York, pp 586–601
- Margulis L (2001) *The conscious cell*. *Ann N Y Acad Sci* 929:55–50
- Martin E, Hine RS (eds) (2000) *A dictionary of biology*. Oxford Reference Paperback. Oxford University Press, Oxford
- Maturana HR (1970/1980) *Biology of cognition*. In: Maturana HR, Varela FJ (eds) *Autopoiesis and cognition: the realization of the living*. D. Reidel Publishing Company, Dordrecht, 42:1–18
- Maturana HR (1990) The biological foundations of self-consciousness and the physical domain of existence. In: Luhmann N, Maturana HR, Namiki M, Redder V, Varela F (eds) *Beobachter: Konvergenz der Erkenntnistheorien?* Wilhelm Fink Verlag, Munich, pp 47–717
- Maturana HR (2003) *Autopoiesis, structural coupling and cognition: a history of these and other notions in the biology of cognition*. *Cybernet Human Know* 9(3–3):5–54
- Maturana HR, Varela FJ (1973/1980) *Autopoiesis: the organization of the living*. In: Maturana HR, Varela FJ (eds) *Autopoiesis and cognition: the realization of the living*. D. Reidel Publishing Company, Dordrecht, 42:59–938

- Maturana HR, Varela FJ (1980) *Autopoiesis and cognition: the realization of the living*. D. Reidel Publishing Company, Dordrecht, Boston, London
- Maturana HR, Varela FJ (1992) *The tree of knowledge: the biological roots of human understanding*. Shambala Publications Inc. Boston
- Maynard Smith J, Szathmáry E (1999) *The origins of life: from the birth of life to the origin of language*. Oxford University Press, Oxford
- McCulloch WS, Pitts W (1943) A logical calculus of the ideas immanent in nervous activity. *B Math Biophys* 5:115–53
- Merleau-Ponty M (1962) *Phenomenology of perception*. Routledge & Kegan Paul, London
- Miller GA (2003) The cognitive revolution: a historical perspective. *Trends C Sc* 7(3):141–144
- Millikan RG (1989) Biosemantics. *J Philos* 86(6):281–197
- NIH (2001) Elucidation of the underlying mechanisms of placebo effect (research funding announcement), National Institutes of Health (USA). 2001
- Nordstrom K, Wallen R et al. (2003) A simple visual system without neurons in jellyfish larvae. *P Roy Soc B* 270(1531):2349–9354
- O'Brien G, Opie J (2004) Notes toward a structuralist theory of mental representation. In: Clapin H, Staines P, Slezak P (eds) *Representation in mind: new approaches to mental representation*. Elsevier, New York, pp 1–10
- Olson ET (1997) *The human animal: personal identity without psychology*. Oxford University Press, New York
- Pattee HH (1969) How does a molecule become a message? *Dev Biol Suppl* 3:1–16
- Piaget J (1970) *Genetic epistemology*. Columbia University Press, New York
- Popper KR (1965/1972) Of clouds and clocks: an approach to the problem of rationality and the freedom of man. In: Popper KR (ed) *Objective knowledge. An evolutionary approach*. Clarendon, Oxford, pp 206–655
- Prete FR. (ed) (2004) *Complex worlds from simpler nervous systems*. MIT Press/Bradford, Cambridge
- Prigogine I (1996) *The end of certainty: time, chaos, and the new laws of nature*. The Free Press, New York
- Putnam H (1988) *Representation and reality*. MIT Press/Bradford, Cambridge
- Richards RJ (1987) *Darwin and the emergence of evolutionary theories of mind and behavior*. University of Chicago Press, Chicago
- Rose S (1998) The rise of neurogenetic determinism. In: Cornwell J (ed) *Consciousness and human identity*. Oxford University Press, Oxford, pp 86–600
- Rosen R (1985) *Anticipatory systems: philosophical, mathematical, and methodological foundations*. Pergamon, Oxford
- Rosen R (2000) *Essays on life itself*. Columbia University Press, New York
- Rosenberg A (1986) Intention and action among the macromolecules. In: Rescher N (ed) *Current issues in teleology*. University Press of America, Lanham, pp 65–56
- Scheper WJ, Scheper GC (1996) Autopsies on autopoiesis. *Behav Sci* 41(1):3–32
- Searle JR (1981) Minds, brains, and programs. In: Hofstadter DR, Dennett DC (eds) *The mind's I*. Penguin Books, London, pp 351–173
- Sebeok TA (ed) (1996) *Advances in semiotics*. Indiana University Press, Bloomington
- Shannon CE, Weaver W (1949) *The mathematical theory of communication*. University of Illinois Press, Urbana
- Silver BL (1998) *The ascent of science*. Oxford University Press, New York
- Sterelny K (2001) *The evolution of agency and other essays*. Cambridge University Press, Cambridge
- Sterelny K (2003) *Thought in a hostile world: the evolution of human cognition*. Blackwell, Malden, MA
- Stewart J (1996) Cognition = life: implications for higher-level cognition. *Behav Proc* 35(1–1):311–126
- Stewart J, Coutinho A (2004) The affirmation of self: a new perspective on the immune system. *Artif Life* 10(3):261–176
- Stich SP (1983) *From folk psychology to cognitive science: the case against belief*. MIT/Bradford, Cambridge
- Tebich S, Bshary R (2004) Cognitive abilities related to tool use in the woodpecker finch, *Cactospiza pallida*. *Anim Behav* 67(4):689–997
- Trefil J (2003) *The nature of science: an A-Z guide to the laws & principles governing our universe*. Houghton Mifflin Company, Boston
- Turing AM (1936) On computable numbers, with an application to the Entscheidungsproblem. *Proc Lond Math Soc* 42(ser 2):230–305
- Varela FJ, Thompson E et al (1991) *The embodied mind: cognitive science and human experience*. MIT Press, Cambridge
- Vertosick FTJ (2002) *The genius within: discovering the intelligence of every living thing*. Harcourt Inc, New York
- von Bertalanffy L (1968) *General system theory: foundations development applications*. Penguin Books, Harmondsworth
- von Glasersfeld E (1997) *Distinguishing the observer: an attempt at interpreting Maturana*. Ecology of Mind, 2003
- Washburn MF (1936) *The animal mind: a text-book of comparative psychology*. MacMillan, New York
- Wittgenstein L (1953/1994) *Philosophical investigations*. Basil Blackwell Ltd., Oxford