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Towards a science of informed matter

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ABSTRACT

Over the last couple of decades, a call has begun to resound in a number of distinct fields of inquiry for a reattachment of form to matter, for an understanding of 'information' as inherently embodied, or, as Jean-Marie Lehn calls it, for a "science of informed matter." We hear this call most clearly in chemistry, in cognitive science, in molecular computation, and in robotics—all fields looking to biological processes to ground a new epistemology. The departure from the values of a more traditional epistemological culture can be seen most clearly in changing representations of biological development. Where for many years now, biological discourse has accepted a sharp distinction (borrowed directly from classical computer science) between information and matter, software and hardware, data and program, encoding and enactment, a new discourse has now begun to emerge in which these distinctions have little meaning. Perhaps ironically, much of this shift depends on drawing inspiration from just those biological processes which the discourse of disembodied information was intended to describe.

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1. Introduction: Form vs. Matter

There is, I think, a sense in which the notion of a science of informed matter is oxymoronic. And that sense has precisely to do with the extent to which modern scientific traditions remain rooted in distinctions between form and matter inherited from classical traditions. In Plato's philosophy, it was form that was the object of the rational knowing mind; matter was the realm of the irrational, the sensual, the chaotic, the indeterminate, the unknowable. For Plato, knowledge required abstraction of the timeless forms out of, and away from, their material manifestations; the intellectual life demanded a "purging of the rational soul from the follies of the body" (Lloyd, 1984, p. 6). Aristotle, like Thomas Aquinas some sixteen centuries later, rejected the equation between form and timelessness, and the associated unknowability of matter, arguing instead for intelligible principles of material things. Yet both Aristotle and Aquinas embraced a genre of the form–matter dualism in their paradigm of knowledge: What mind can grasp are the principles of material things, not the things themselves, and these principles retain the universality, immateriality, and immobility of Platonic forms. As Aquinas wrote, "there is nothing to hinder our having an immovable science of movable things" (1274).

Echoes of these earlier traditions can be heard throughout the halls of modern science. They can, e.g., be found in Steven Weinberg's defense of physics as the search for the fundamental (timeless) laws of nature against Wolfram's plea for a new science, a science based not on simplicity but on complexity. As Weinberg writes, "Wolfram makes it seem that physicists choose simple rather than complex phenomena to study because of long habit or mathematical flabbiness, but in seeking the laws of nature it is the essence of the art of science to avoid complexity." While he acknowledges that the "free-floating theories" that Wolfram and his colleagues have on offer are interesting and important, they are not truly fundamental, because they may or may not apply to a given system; to justify applying one of these theories in a given context you have to be able to deduce the axioms of the theory in that context from the really fundamental laws of nature" (2002). Indeed, it might be said that Weinberg's very search for the fundamental essence of matter in elementary particles, or rather, in the fields that generate them—in entities that persist self-identically in time—is itself a project that owes its underlying rationale to such

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classical understandings of knowledge. The material world, according to this vision, is reconstituted by adding the relevant forces to form higher order structures—i.e., structures that, like the particles of which they are constituted, can also persist as self-identical[1].

2. Information

I cannot begin to do justice here to the huge literature on the different notions of information currently in use in mathematics, computer science, physics, and biology that exists, and I make no pretence to doing so. Nevertheless, in the essayistic style of the present discussion, I would like to suggest that similar echoes of ancient form–matter dualisms can also be found in information theory and in computational science. Let me start with information theory: Classically (at least since Shannon), the information content (or entropy) of a physical system is the number of bits required to specify its microstate; it is a measure of the uncertainty of that state and is determined by the probability of its configuration. This quantity qualifies as information in a very particular sense: it is 'informative' relative to questions posed by a human observer performing measurements on that system. For example, measurement of the spin of an electron will provide one bit of information: it will answer the question, is the spin up or down? Crucially, the answer to such a question—an answer obtained by the measurement we perform—need not itself have any bearing on the subsequent behavior of the system in which it is embedded: any particular bit of the information contained (or registered) in a system may or may not be relevant to (or informative about) its ensuing fate. For a bit of information to be informative with respect to the system's own development entails a concept of information that seems to me to be *prima facie* different: information *for* rather than information *about*, loosely corresponding to Gregory Bateson's definition as a difference that makes a difference, rather than to Shannon's notion of information as entropy. To disambiguate the term, I will refer to difference making information as *EI*, or effective information, and the quantity usually referred to in information theory as *SI*, or Shannon (entropic or structural) information. The question now arises: How do we know how much of all the available structural information is effective? Clearly, if we are to be able to say whether any particular bit of information is effective, we must specify the context in which that bit of information is embedded, the larger system in which it finds itself and with which it is in interaction. We must say with respect to what that information might or might not make a difference. In other words, we must situate our bit of information in its material context. Once that context is specified, it should be empirically straightforward to determine whether or not changing a particular bit of information makes a difference (relative, of course, to the level of discrimination) (see, e.g., Lloyd, 2007). But while the total amount of information contained in a well-delineated system (its *SI*) is a property of the structure of that system, taken by itself, effective information is a property of both the internal dynamics of that system and its relation to its environment—whether or not a bit of information is effective depends crucially on the particular entities or environment with which the system interacts, and to which a difference may or may not be effected.

More generally, one might say that the total information content of a system (its *SI*, or entropy) is a quantity abstracted away from the material world in which that system is embedded (this is at least one of the senses in which *SI* is commonly said to be 'meaningless'). *SI* is also often understood as abstracted away from the actual stuff of which that system is constituted. It is the system's form or structure, where the stuff of which that system is constituted merely provides the substrate in which the information is 'encoded'. To quote Howard Resnikoff, information (*SI*) is what "remains after one abstracts from the material aspects of physical reality" (1989). By contrast, the effective information in a system is not only dependent upon the material reality in which it is embedded, but may actually be newly created (in the sense that previously ineffective information can be made newly effective) by a novel context[2].

There remains the crucial question of the kind of difference that is made, and the "value" of that difference to the system in question. In particular, the question of what relation, if any, *SI* might have to the various notions of semantic information that have been proposed as being of relevance to biological systems. For example, Jablonka (2002) has proposed a notion of biological information that is similarly relational, but that is specifically limited to functional information. By my account, functional information would be a subset of *EI*, limited to the effecting of those changes that contribute to fitness and hence can be singled out by natural selection.

3. The move towards embodiment in computer science and cognitive science

The distinction between SI and EI, between structural and effective information, bears some striking parallels with a set of distinctions that a number of computer scientists have (more or less independently) recently introduced, and I want to argue that they signal the beginnings of a distinct break from one, relatively formalistic, tradition and the forging of another; the crafting of a new epistemological culture in which form is always and inextricably material, and matter always and inextricably informed. In an early foray of this kind, David Harel and A. Pnueli introduced the term reactive system in 1985 to refer to a class of developing complex systems that were proving particularly problematic in relation to conventional methods, and to distinguish them from the familiar sequential (or transformational) systems of traditional computer science: "A transformational system accepts inputs, performs transformations on them and produces outputs . . . Reactive systems, on the other hand, are repeatedly prompted by the outside world and their role is to continuously respond to external inputs. A reactive system, in general, does not compute or perform a function, but is supposed to maintain a certain ongoing relationship, so to speak, with its environment" (1985, p. 479). And just a few years later, a related distinction began to emerge in efforts to build autonomous robots capable of functioning in uncertain environments. For Rodney Brooks, one of the chief architects of the new robotics, emphasis on design principles incorporating the dynamics of direct interactions with the world lay at the root of the divergence between his approach and that of traditional robotics and Artificial Intelligence lay in his. As Brooks explained (1992, p. 1227),

[1] The critique of the notion of 'substance' as an entity that endures "self-identically" is most familiarly associated with Alfred North Whitehead who wrote, e.g., "The simple notion of an enduring substance sustaining persistent qualities, either essentially or accidentally, expresses a useful abstraction for many purposes of life. But whenever we try to use it as a fundamental statement of the nature of things, it proves itself mistaken" (1929, p. 109). Many of the arguments discussed below might be said to follow from questions like, what if Whitehead was right? What if there is no level of things that endure self-identically? Or, what if there is no immediately relevant level of things that endure self-identically? What if there are many stable configurations (depending on context), perhaps undergoing constant transitions, in which the behavior of the composite entity depends on its configuration (and, by implication, on the environment in which it finds itself)? As, e.g., appears to be the case for the behavior of proteins?

[2] See, e.g., the argument by Keller & Harel (2007) for the importance of the development of cellular processes that make use of DNA sequence information in new ways, without requiring changes in that sequence.

There are two subtly different central ideas that are crucial and have led to solutions that use behavior-producing modules:

- *Situatedness:* The robots are situated in the world—they do not deal with abstract descriptions, but with the "here" and "now" of the environment that directly influences the behavior of the system.
- *Embodiment:* The robots have bodies and experience the world directly-their actions are part of a dynamic with the world, and the actions have immediate feedback on the robots' own sensations.

Such arguments, coming both from computation and from robotics, have acquired considerable weight over the last 20 years. Harel and Pnueli's early distinction between reactive and transformational systems has been extended, renamed, and embedded in a more general plea for a new computational paradigm. For example, in a recent collection of articles on Interactive Computation (Goldin, Smolka, & Wegner, 2006), the authors argue for the need to move a beyond Turing machines (described as closed systems) to interactive machines (open systems). In Turing machines, the result of a computation depends only on the internal state of the machine and the (specified) input, whereas interactive machines operate on inputs from a dynamical environment that is directly linked to the machine in question but that may or may not itself be describable by a computable function (and may or may not be predictable). The term "interactive machine" was first introduced by Wegner (1995) to emphasize the role of computers as active agents that directly effect and collaborate with other active agents. As Farhad Arbab explains, "What distinguishes an interactive system from other concurrent systems [multi-tape Turing machines] is the fact that an interactive system has unpredictable input from the external environment that it does not control" (Arbab, 2006, p. 16). In the same volume (and the same spirit), Robin Milner advocates a shift in our understanding of software from a prescription for how to do something (a list of instructions) to a description of behavior, and he asks us to "think of the term 'information' actively, as the *activity of informing*." (2006, p. 7; italics in original). The net effect, writes Lynn Stein, is to change the way we think about computation itself: "Computation is not a sequence of steps to produce a result at the end. Computation is embodied in ongoing interactive entities. It is composed of a community of such entities; their interactions are what make computation happen. Input is what you observe; output is what you do. Computations are evaluated based on ongoing behavior, commitments kept, services provided, invariants maintained" (2006, p. 482).

As Stein observes, the shift to interactive computation has close parallels in other disciplines, albeit often under different terminology. Robotics, discussed above, is perhaps the most obvious example. Under the keyword "embodied artificial intelligence", a literature about design principles that exploit system–environment interaction and make use of embodiment has mushroomed over the last two decades. Following in the footsteps of Rodney Brooks, much of the more recent work on adaptive robotics draws explicitly on biology for inspiration. Thus, for example, Pfeifer, Lungarella, and Iida (2007, p. 1088) emphasize that "robots having to perform in the real world should be able to cope with uncertain situations and react quickly to changes in the environment. Biological systems provide an exceptional source of inspiration." As in biological systems, they explain, behavior is, first,

> "effected by the ecological niche in which the system is physically embedded, by its morphology, ... and by the material elements composing the morphology. Second, physical constraints shape the dynamics of the interaction of the embodied system with its environment ... and can be exploited to achieve stability, maneuverability, and energy efficiency" (ibid).

And in a closely related endeavor, Estévez and Lipson employ the term "developmental system" to describe "a generative process that produces a phenotype whose form depends on feedback obtained from the environment during development" (2007, p. 238). Their particular aim is to extend earlier work on reactive developmental systems, in which the system responds to the environment, to interactive developmental systems in which (as is so often the case in biological development) the environment also and simultaneously responds to the output of the system.

The term Cognitive Science refers to an interdisciplinary approach to the study of mind that was initially forged in the 1950s. Its subject is human rather than machine intelligence, but its guiding inspiration came from analogizing the one to the other; indeed, the field was built around the assumption that human cognition could be effectively likened to the principles of symbol-based artificial intelligence and its early development was intimately tied to the paradigms of computer science and artificial intelligence that originally prevailed. It is thus of particular interest that early reactions against the metaphoric equating of mind and computer, arguments against the relevance of traditional theories of computation to human intelligence, have now grown into a strong and increasingly influential research program in psychology that closely parallels the newer developments in robotics and computer science that I have been discussing. Of particular importance to this research program (often referred to as one of Embodied Cognition) is the formative role played by organism–environment interactions in the development of human cognition, and more specifically, the dependence of cognitive development on real-time interactions between the physical configuration and activities of the organism and the environment to which it is so tightly coupled (see, e.g., Thelen, 1995; Thelen, Schoner, Scheier, & Smith, 2001; Varela, Thompson, & Rosch, 1991). Strongly influenced by Merleau-Ponty, the central assumption here is that embodiment, understood in terms of the organism's sensorimotor capacities, as what enables that organism to conceptualize, to categorize, or to otherwise interact effectively with its environmental niche.

4. A science of informed matter

But the call for a "science of informed matter" with which I began comes from an altogether different quarter. It comes not from computer science, nor from cognitive science, and not even from biology; it comes instead from chemistry. More specifically, it comes from the field that Jean-Marie Lehn has dubbed "supramolecular chemistry", and that his own efforts have been so important in establishing. The focus of supramolecular chemistry, largely inspired by the self-assembly of proteins and protein complexes in biological systems, is the spontaneous self-organization, *in vitro*, of any complex (often functional) molecular systems out of simple molecular components. The motor driving such self-assembly is molecular recognition, which Lehn describes as "binding with a purpose, like receptors are ligands with a purpose. It implies a pattern recognition process through a structurally well-defined set of intermolecular interactions" (1995, p. 11). It also implies, he continues, "the (molecular) storage and (supramolecular) read out of molecular information" (ibid). Thus supramolecular chemistry "may be considered as a *chemical information science* or *molecular 'informatics'*" (p. 12, italics in original)—or, as he elsewhere puts it, a "science of informed matter."

The particular question I want to ask is, how are we to understand the term information as Lehn uses it here? What does he mean by "informed matter"? My claim is that the primary reference to information in Lehn's work (as well as in that of his followers) has, from the very start, been to the term in Bateson's sense—i.e., to effective information, to a difference which makes a difference; furthermore, I suggest that the basic ambiguity that haunts this term elsewhere also infects Lehn's vision of chemistry as an information science. Nevertheless, I claim that the focal point of Lehn's vision has clarified over the years, perhaps especially so in response to recent shifts in attention to dynamic supramolecular chemistry, in the process becoming more decisively aligned with the notion of information as effective, embodied, and critically dependent upon the environmental context in which the molecular system finds itself. The net effect is a striking parallel with the shifts we have been observing in computer science, robotics, and cognitive science, occurring over roughly the same period. To make this case, I want to read and analyze some excerpts from his work:

In one of his earliest papers on the subject, "Perspectives in Supramolecular Chemistry—From Molecular Recognition towards Molecular Information Processing and Self-organization" (1990), Lehn emphasizes the storage of "molecular information" in the receptors of individual molecules, and the formation of devices "for signal and information processing at the molecular and supramolecular levels" (p. 1304). As he writes, "a common thread of all areas of supramolecular chemistry is the *information* stored in the structural (and eventually temporal) features of molecules and supramolecules. Thus, it is a kind of *molecular information science*" (p. 1305). Furthermore, "The information necessary for [self-assembly and self-organization] to take place and the algorithm (the "Aufbau" rules) that the process follows must be stored in the components and operate via selective molecular interactions. Thus, these systems may be termed programmed molecular and supramolecular that generate organized entities following a defined plan based on molecular recognition events." (p. 1311).

Repeatedly, we are told that the information required to generate the larger organized entities in question is "stored" in the component receptor elements of individual molecules; this information is in turn processed by rules (or "algorithms") also 'stored' in individual components, but which 'operate' by way of molecular interactions. The production of supramolecular thus proceeds according to 'programs' specified by individual components, yet "based on" molecular recognition events. But there is an important ambiguity here. What kind of information can be stored in the conformation of receptor elements? On the one hand, we are invited to think of this information in the original sense of information as entropy, i.e., as the number of bits required to specify its particular microstate. On the other hand, however, the only information that is relevant to the generation of supramolecular entities is the effective information, and this depends not only on the conformation of a particular site on an individual molecule but also on whether or not the configuration is recognizable. And that, the question of how much of the structural information available is recognizable (in my language, how much of it is effective) is relational; it depends not on our knowledge of the system (i.e., not on our capacities for recognition) but on what other molecules are available in the vicinity as potential recognizers. Thus, the information that Lehn describes as 'stored' in individual receptors is at best only potential information; for it to become informative (or effective), to make a difference—that requires recognition by other molecules. In other words, the information that matters for Lehn's purposes, the capacity of a molecular site to be informative, to 'in-form' the structure of the supramolecular entities, cannot properly be said to be stored in individual molecules; indeed, if we must speak of effective information being stored, we would have to say it is stored in the relations, in the interactions, in the embodied context of those molecules. I suggest, however, that it would be better to dispense with the language of storage altogether (and with that notion, the related circumlocutions of representation and encoding) and speak instead simply of the capacities of material entities to shape, inform, and effect other material entities with which they come into contact.

Lehn too refers to supramolecular assemblage as "in-formed", thereby tacitly shifting the meaning in just the sense that I am arguing for. Furthermore, clarification of this distinction in usage also allows us to make sense of another point that he makes later in the same text, where he refers to the "*amplification* of molecular ... information from the microscopic to the macroscopic level" that accompanies the process of self-assembly (p. 1314, emphasis in the original). The important point here is that while *EI* can be self-amplifying, *SI* is not. That is, not when the latter is defined as the number of bits required to specify the microstate of the system[3]. But the capacity of molecules to inform the molecules around it, in ways that allow those molecules to, in turn, shape and inform the entities with which they come into contact can and often does lead to an increase in the system's overall capacity to inform. This in no way undermines our ability to influence this process by tweaking the constituent ingredients. For practical purposes, for the new horizons that Lehn envisages, i.e., for the purposes of designing new "molecular-information-dependent, *informed*, and functional self-organizing systems" (1990, p. 1317), one works with what one has at hand, tinkering with this relational information by manipulating the component structures, by introducing differences in individual molecules that make a difference down the line. Nor does it either alter the fact that the locus of the effective information is in the interactions, or undermine the clear implication that the "molecular information science" or "molecular informatics" to which Lehn refers (p. 1317) must be understood as something quite distinct from classical information theory.

The primary subject of this early paper may well be said to have been "programmable" self-assembly, but over the years since, supramolecular chemistry has moved well beyond the realm of programming and design. It has moved into a domain in which a flux of energy through the system supports continuous breaking and reforming of inter-molecular bonds, ongoing reorganization and exchange of component parts, all of which allows for the emergence of adaptative and evolutionary chemistry based on internal selection. As he explains,

> "This behaviour [of reversible forming and breaking of bonds] defines a constitutional dynamic chemistry that allows self-organization by selection as well as by design at both the molecular and supramolecular levels. Whereas self-organization by design strives to achieve full control over the output molecular or supramolecular entity by explicit programming, selforganization by selection operates on dynamic constitutional diversity in response to either internal or external factors to achieve adaptation in a Darwinistic fashion.
>
> The merging of the features, information and programmability, dynamics and reversibility, constitution and structural diversity, points towards the emergence of adaptative and evolutionary chemistry. Together with the corresponding fields of physics and biology, it constitutes a science of informed matter, of organized, adaptative complex matter. " (2004, p. 250).

The shift to non-equilibrium dynamics allows for a great expansion in Lehn's vision, and its accommodation of a kind of selection is key to this expansion. It is this that allows Lehn to speak of adaptation, function, and evolution, and of others to speak of "learning by matter"[4]. It is also what provides the grounds for a rapprochement with

[3] There are however times when information/entropy is defined as the measure of our ignorance (see, e.g., Lloyd, 2007, Chapter Four). In that case, it too can grow, for defining it so makes entropy a relational quantity as well, albeit in a different sense: it is relational to us as observers, rather than to the physical systems with which it interacts independently of our observations (that is, with which it interacts classically rather than quantum-mechanically).

[4] See, e.g., Brakmann (1997), whose notion of "pragmatic information" is closely related to the notion of *EI* used here.

the visions of adaptive robotics and embodied cognition. And more yet: it permits him to foresee a closing of the gap between the living and the non-living that has for so long underlain all our scientific thinking about life and matter[5]; that gap is closed, he writes, by "a sort of prebiotic Darwinism driven by self-organisation [in which internal] ... selection of the components [yields] the "fittest" constituent" (2007, p. 155). The dynamics of ongoing assembly and disassembly provides the key to his vision of a smooth progression from the Big Bang to thinking beings, all "under the pressure of information":

> How matter is becoming and has become complex is the most fundamental question raised to science, for it indeed asks how (and why?) the evolution of the universe has given rise to an organism capable of asking this very question and of generating the means to answer it by creating science (2004, p. 251).

More specifically, he should have written, by creating "a science of informed matter".

The concluding figure of his 2004 paper summarizes Lehn's idea of just what "a science of informed matter" can do for us:

of its science a name of its own. That name is of course biology. But ever since, the splitting off of biology from the physical sciences has posed an apparently insurmountable problem for committed materialists: On the one hand we agree that life is nothing more than physical and chemical processes; on the other hand, for all the successes physicists and chemists have achieved in explaining many biological processes, no account developed over these last two centuries has been able to answer the question, "What is the difference between a live cat and a dead one?[6]" No physical–chemical model has yet been proposed for the spontaneous evolution of a system with function and purpose. No Newton of a blade of grass has yet to appear in our midst.

Is it possible that the difficulty has lain in the initial formulation? When biology was first separated from the physical sciences, the partition was thought to be mandated by the special organization characterizing living organisms. The term organization, I suggest, served 19th century biologists much as form had served ancient Greek philosophy. For Aristotle, e.g., the essence of any living thing is its form or *Anima*, the primary attribute of a naturally organized body. Matter itself (the female contribution to generation) is passive; form (the male contribution) provides the

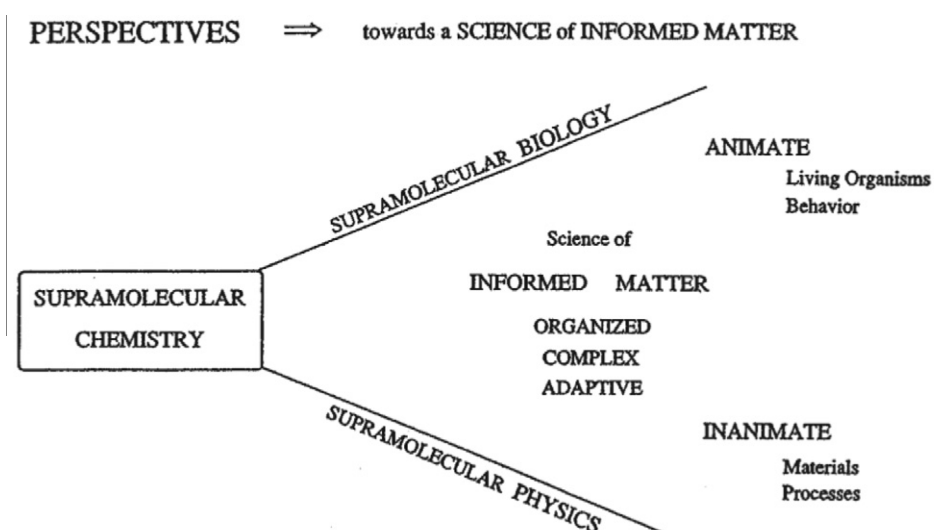

Figure 12. Supramolecular science as the science of informed matter. Supramolecular chemistry at the interfaces of biology and physics.

5. Conclusion

It is just a little more than 200 years ago that the subject of the life sciences was adjudicated to be sufficiently distinct as to require

activating principle—as it were, the life force. Two millennia later, in the discourse of modern science, matter was still cast as passive, with activity/dynamics provided by the forces that act upon it. But the forces with which physics is familiar seem somehow inade-

[5] Implicitly, at least, it even raises the question of the extent to which this gap is predicated on the split between form and matter that Lehn's formulation—at least as I read it—seeks to heal.

[6] This was the question posed in a recent *Nature* editorial as the defining quest of Systems Biology (5 May 2005, Vol. 435, Issue No. 7038, p. 1).

quate to impart matter with the activity that makes it vital; with the kinds of organization that distinguish living beings from the world of the non-living[7].

J.B. Lamarck was one of the first to distinguish the science of living forms as Biology, and also to characterize the vital distinction as one of organization. Ironically, however, Lamarck himself never doubted that such organization was material, a product of natural forces. ''Nature has no need for special laws,'' he wrote; in fact, he intended biology to be ''an enquiry into the physical causes which give rise to the phenomena of life.''

What supramolecular chemistry, robotics, interactive computation, and embodied cognition bring to the discussion is a shift in perspective which, I suggest, goes a good distance towards annulling the very gap between living and non-living with which we have been have been struggling for so long. In this perspective matter is not passive, but always already active; furthermore, it is so by virtue of being always already in form. For information to be relevant to the dynamics of a system, it must be informative. As Robin Milner invites us to think of the term, we begin to see 'information' as inseparable from ''the *activity of informing*.'' The very form in which a molecule (or any other configured structure) finds itself imparts to it the capacity to actively inform other molecules or structures, thereby setting off the chain of interactivity on which Lehn's vision of a smooth progression from the Big Bang to thinking beings.

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[7] J.B. Lamarck was one of the first to distinguish the science of living forms as Biology, and also, to characterize the vital distinction as one of organization. Ironically, however, Lamarck himself never doubted that such organization was material, a product of natural forces. ''Nature has no need for special laws,'' he wrote; in fact, he intended biology to be ''an enquiry into the physical causes which give rise to the phenomena of life.'' Moreover, his view of the processes that give rise to the phenomena of life seem to bear far greater affinity to supramolecular chemistry than to the physics of his time. Consider, e.g., his introductory statement about the ''physical causes of life'':

> All physical bodies whatever—solid, fluid, liquid or gaseous—are endowed with properties and faculties peculiar to themselves; but as a result of the movement distributed among them, these bodies are liable to different relations and transformations in their state and position. They are liable to contract with one another various kinds of union, combination or aggregation, and then to undergo all kinds of alterations, such as complete or incomplete separation from their other components or from their aggregates, etc.; these bodies thus derive new properties from the condition in which each of them is placed. (1809, Part II, Introduction, p. 183. Translated by Hugh Elliot, 1914, Macmillan and Co. Ltd.)