How (not) to be a reductionist in a complex universe

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1. Introduction

In the last 10 years the reductionism debate has shifted to the idea of reduction as a relation not between *theories*, but between *explanations*. A reductionist explains a system's phenomenon by the properties and interactions of its components. Through this move Sahotra Sarkar attempted to shift attention from a discussion of the logical form of scientific theories to questions regarding the interpretation of scientific explanations (Sarkar 1998). During this time there has been a spate of publications on what has variously been termed 'causal', 'proximal', or 'experimental' biology, including Sahotra Sarkar's *Molecular Models of Life*, Marcel Weber's *Philosophy of Experimental Biology, William* Bechtel's *Discovering Cell Mechanisms* and Alexander Rosenberg's *Darwinian Reductionism* (Sarkar 2005; Weber 2005; Bechtel 2006; Rosenberg 2006). Among the emergent themes in the recent literature on proximal biology are: 1. Does proximal biology discover 'mechanisms' rather than laws or theories? 2. What is the relationship between physicalism and antireductionism? 3. How does proximal biology deal with levels of organization, complexity and non-trivial emergence? In the light of these and other themes this paper discusses to what extent should we expect biological phenomena to be reduced to the molecular level. While most philosophers of biology, and arguably biologists as well, subscribe to some kind of physicalism they also belief that biological phenomena in principle cannot be reduced to physical ones. However, some reductionists, notably Alex Rosenberg, have pointed to the alleged paradox, or "untenable dualism", between physicalism and antireductionism (Rosenberg 2006).

Based on some contemporary ideas in foundational physics this paper will first show that not only are physicalism and antireductionism compatible but that knowledge of certain physical principles - that show remarkable independence from micro laws governing smaller particles – must lead to such a move. This section leads away from the mainstream multiple realizability argument for non-reductionism to the argument from the physical principle of organization and collective behavior. The second section argues that this non-reductionism still allows for the legitimate commitment to *methodological* reductionism complementing an *explanatory* non-reductive strategy. The last section will apply the conclusion drawn in the previous sections to interpret the recent move from molecular biology to postgenomic biology. It was indeed no paradox that the success of reductionist biology ultimately lead to the conviction that a deep understanding of living systems needs both the knowledge of the component microproperties and the insights of a top-down approach into the system's macroproperties from systems biology.

2. Antireductionism and Physicalism

Rosenberg's demand for a reductionistic biology rests on the metaphysical thesis of physicalism and the claim that non-reductionistic explanations are incompatible with physicalism. (In contrast to the recent move in philosophy of biology to demand biological explanations in terms of mechanisms Rosenberg insists on nomological-deductive explanations). Physicalism is sometimes interpreted as the 'causal closure' or 'completeness of physics' principle, which holds that all physical events are determined by the fundamental laws of physics (Bishop 2005), or as the assumption that all worldly phenomena are nothing but 'matter in motion'. I want to contrast this stance towards worldly phenomena with 'matter (not just in motion but) in organization', a stance taken up by some non-reductionist physicalists. There is more to physics than reduction to quantum mechanics, relativity theory and an elusive Theory of Everything.

Probably most biologists, often without basic knowledge of physics, believe that physics is in itself the most reductionist of sciences. This is by no means true for all physicists. The drift away from reductionism is most pronounced among condensed matter and low energy physicists who claim that for most worldly phenomena the Standard Model or the illusive Theory of Everything would be unable to explain what we deem interesting about them. Some argue for a hierarchy of more or less independent Effective Field Theories (Castellani 2002). A heterogeneous group of physicists attempt to define general physical principles that defy reductionism by their transcendence and independence of microscopic laws (Anderson 1972, 2005; Charap 2002; Laughlin and Pines 2000; Laughlin 2005; Ellis 2006). It is still the case that "to other kinds of scientists the idea is considered dangerous and ludicrous, for it is fundamentally at odds with the reductionist beliefs central to much of physics. But the safety that comes from acknowledging only the facts one likes is fundamentally incompatible with science" (Laughlin and Pines 2000, 30).

Who are to enact that the laws governing the behavior of particles are more ultimate than the transcendent, emergent laws of the collective they generate, such as the principles of organization responsible for emergent behavior? According to the physicist George F. R. Ellis true complexity emerges as higher levels of order from, but to a large degree independent of, the underlying low-level physics. Order implies higher-level systemic organization that has real top-down effects on the behavior of the parts at the lower level. Organized matter has unique properties (Ellis 2004). In the same vein the two Nobel laureates and Stanford professors of physics Phillip W. Anderson and Robert B. Laughlin have both challenged the prevailing reductionist strategy of modern science. While the former identifies contingent symmetry breaking features providing new ontologies and concludes *More is different* (Anderson 1972), the latter asserts that laws and theories follow from collective behavior, not the other way around. If we try to analyze things too closely, we risk not understanding how they work on a macro level. Together with David Pines Laughlin claims that "the triumph of the reductionism of the Greeks is a pyrrhic victory: We have succeeded in reducing all of ordinary physical behavior to a simple, correct Theory of Everything only to discover that it has revealed exactly nothing about many things of great importance" (Laughlin and Pines 2000, 28). They point to higher organizing principles in nature, e.g. the principle of continuous symmetry breaking, localization, protection, and self-organization, that are insensitive to and independent of the underlying microscopic laws and often solely determine the generic low-energy properties of stable states of matter ('quantum protectorates') and their associated emergent physical phenomena. "The central task of theoretical physics in our time is no longer to write down the ultimate equations but rather to catalogue and understand emergent behavior in its many guises, including potentially life itself. We call this physics of the next century the study of complex adaptive matter" (Laughlin and Pines 2000).

From this existence of new laws of nature that become operational only at more complex levels of organization I deduce that 'fundamental' laws governing the behavior of parts are necessary but not sufficient to explain systemic phenomena. The latter are conditional on the contingent context set by physics, chemistry or biology causing emerging principles, together with which they form sufficient conditions for the systemic properties we wish to explain. It is important to note that these newly emerging forces don't contradict contemporary physics, a physics consisting of a hierarchy of laws that emerge out of complexly organized matter, instead of being 'nothing but' a final quantum theory of gravity. Only when this truth sinks in will the reductionist camp of the life sciences agree to embrace complexity.

3. Two Kinds of Reductionist Strategies

There are different research foci at work and depending on them a reductionist methodology and explanatory strategy may be a poor or the proper choice. One example is the focus on genes and genomes in molecular biology not because of their proposed (but unsupported) unique ontological status but because of their unique manipulability due to their stereo-chemical and digital properties. To deduce from these properties, however, the special status of genomes as programs that reductively explain development and all bodily functions is not a logical conclusion. A reductionist methodology and even explanatory strategy can have its virtues when focusing on computation, engineering, simplification and manipulation, but has its vices when trying to extrapolate illegitimately from a limited base of knowledge. Reductionism is a central epistemic strategy, and since every system can in principle be analyzed through the behavior of its components such a strategy is always possible. It is nevertheless unclear, and as I argue rather unlikely, that reductionism always delivers the only possible, the most satisfying, or the most complete explanation of a phenomenon.

In most definitions or understandings of reductionism the explanatory arrows points downward (Weinberg 1987). But is the best and most parsimonious choice in science always to explain phenomena by lower physical laws? The reductionist approach tends to ignore a crucial feature that enables the emergence of biological complexity out of the underlying physical substratum, namely, top-down action in the hierarchy of complexity that affects both the context and nature of constituent parts. What occurs is causally efficacious contextual emergence of complexity (Bishop 2005; Craver and Bechtel 2006). Instead of always choosing the simplest explanation one may want the most complete and encompassing one. Jason Scott Robert, for instance, has asked if development should be reduced to developmental genetics or molecular biology, or if indeed the latter should both be 'reduced', or better, integrated into a more complete theory of development. He argues convincingly that the genetic explanation does not explain the original problem (development) but a sub-problem (the role of genes in development) (Robert 2004).

Rosenberg in his *Darwinian Reductionism* neglects to discuss the many forms of emergence (weak, strong, nontrivial) and the various commitments to reductionism that go along with them. The book defines the reductionistic program of molecular biology as the belief that all biological phenomena must in principle be fully reducible to the scientific laws recognized by physics and chemistry - notwithstanding the contestability of the reduction of chemistry (Bishop 2005; Luisi 2002); there *is* nothing more to biological facts than the interaction of macromolecules that bring them about. Here Rosenberg implicitly refers to ontological reductionism. At another place we are informed that biological explanations need to be "improved, corrected, strengthened, made more accurate and adequate, and completed" by molecular biology (Rosenberg 2006, 4). This statement, however, translates the former into biological practice and therefore refers to epistemological reductionism. As not just a matter of practical limitations on our ability to carry out reductions but a view about scientific theorizing, it includes methodological and explanatory reduction (Feest 2003; Jones 2004). Without appreciating the difference between investigative and explanatory strategies one couldn't understand that a biologist may follow molecular research methodologies while at the same time seek a full explanation by including non-reductive approaches. Hence her explanation would be non-reductionistic while still grounded in molecular biology and microscopic physical laws that provide necessary but not sufficient conditions for the emergent phenomenon accounted for in the explanation.

Niels Bohr's and Max Delbrueck's quest for complementarity and new laws of physics in biology, which both held before being lured in by the early successes of molecular biology, is an example of such a strategy (Vol'kenshteĭn 1988). Both shared the belief that at least some aspects of life are not reducible to physico-chemical terms; mechanistic and teleological descriptions should be understood as mutually exclusive yet jointly necessary for an exhaustive understanding of life (McKaughan 2005). Phillip Anderson has distinguished the legitimate "reductionist hypothesis", "the ability to reduce everything to simple fundamental laws" from the fallacious "constructionist hypothesis", that argues for "the ability to start from those laws and reconstruct the universe" (Anderson 1972, 393).

4. From investigative reductionism to holist explanations in biology

> "In the 1940's, J. H. Woodger (1948) argued that biologists should only use biological facts to explain other biological facts, and that they certainly should not reduce them to the concepts of physics and chemistry. (…) But the decoding of the "language of life" by Watson and Crick was not achieved by adhering to the various doctrines of biological ontological autonomy, nor could it possibly have been. (…) Woodger's biology was revolutionized by an exploration of the atomic structure and chemistry of the DNA molecule. Indeed, the central concepts of these disciplines (ions in chemistry, genes in biology) have their origins in what was once dismissed as reductionist science." (Walsh 1997, 125)

Equating the discovery of the molecular structure of DNA with the "decoding of the 'language of life'" or similarly overstated metaphors is a typical 'argument' for reductionism in biology. Strangely many biologists and non-specialists alike seem satisfied with accepting the existence of 'genes' as the ultimate explanation of life. How can detecting the chemical structure of one macromolecule uncover the 'secrets of life' when all it does is carrying template capacities for important cellular ingredient? By transferring the near mystical powers people had attributed to the placeholder in a biological theory to explain the transmission of biological form, termed 'genes', to the macromolecule DNA and neglecting to provide the molecular mechanisms of the emergence of life through the mere existence of DNA. This is no reductionist success story but an example of "astrological science" (its not in the stars, its in the genes) (Barnes and Dupre Manuscript). To answer how the complexity of life emerges from its underlying simplicity, however, is the real challenge of the life sciences of the 21st century. These 'fundamental principles of life' must go beyond the Darwinian process of evolution and the genetic code; DNA just provides sequestered templates from which advanced living system build some of life's building block, and natural selection is itself an emergent phenomenon resulting from the origin of non-linear dynamical systems that exhibit the central properties of metabolism (the channeling of energy), cellularity (individuality through membranes), reproduction and adaptability (production of heritable variation).

The extraordinarily successful reductionist approach of present day physics and molecular biology is based on the concept of an isolated system. But in the real world all parts show high sensitivity to context; hence context matters beside laws and other regularities. Even though systems are ultimately constructed out of their components how should one think about 'parts' without envisioning (their constituent function for) the whole system? The system itself produces top-down effects that influence its components' behavior. Craver and Bechtel translate interlevel causes (both bottom-up and top-down) into mechanistically mediated effects that are hybrids of causal and constitutive relations (Craver and Bechtel 2006). Wholes and parts are constitutive of each other. The same macromolecules acting in isolation or in an integrative whole have - sometimes radically - different effects due to their recruitment into different networks of interacting parts. This difference between *molecular* and *cellular* functions of molecules creates one of the challenges for reductionist research strategies. The ways in which the same molecules function differently in different networks and how they produce emergent behavior at the systems level because of the way the system is organized is just one phenomenon that the sciences of complexity, postgenomics and systems biology attempt to tackle.

The genome sequencing project revealed that humans possess a modular set of ca 21,000 protein-coding genes from which the body can fashion two orders of magnitude more products. And while genomics, proteomics, transcriptomics, metabolomics and other ~omics are in the process of mapping the complete inventory of living cells, newly emerging sciences are left with the lingering question of how to reassemble these constituents to form complex living systems (Stotz 2006, submitted).

> "For better or worse we are now witnessing a transition from the science of the past, so intimately linked to reductionism, to the study of complex adaptive matter, firmly based in experiment, with its hope for providing a jumping-off point for new discoveries, new concepts, and new wisdom." (Laughlin and Pines 2000, 30)

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