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A Hierarchical Architecture for Nano-scale Science and Technology: Taking Stock of the Claims About Science Made By Advocates of NBIC Convergence

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Abstract. Leaders of nanoscale science and technology advance a systems theoretic model as an alternative to scientific reductionism. Within this essay, I seek to formulate their concerns in a more philosophical idiom, and thereby provide a basis for a common discourse about the nature, values, and limits of current science. This will be of special importance as we contemplate the radical capacities for human enhancement made possible by converging technologies.

The evolution of a hierarchical architecture for integrating natural and human sciences across many scales, dimensions, and data modalities will be required. Half a millennium ago, Renaissance leaders were masters of several fields simultaneously. Today, however, specialization has splintered the arts and engineering, and no one can master more than a tiny fragment of human creativity. The sciences have reached a watershed at which they must unify if they are to continue to advance rapidly. Convergence of the sciences can initiate a new renaissance, embodying a holistic view of technology based on transformative tools, the mathematics of complex systems, and unified cause-and-effect understanding of the physical world from the nanoscale to the planetary scale. (Roco & Bainbridge 2002, p. x)

Introduction*

A new capacity to measure and directly manipulate matter at the nano-scale establishes the conditions for a convergence between physics, chemistry, biology, and the engineering disciplines that use these sciences to address human needs. On the basis of this nano-scale convergence, a higher level convergence is made possible, one which offers great promise for human enhancement. At this higher level, nano-science and technology merges with biomedicine, information technology, and cognitive science. In order to seed the development of this NBIC convergence (Nano, Bio, Info, and Cogno), and to assure that it is appropriately directed for human enhancement, a major public/private partnership is being formed. Millions of dollars will be used to establish and organize the infrastructure needed.

The principal architects of the convergence effort argue that one of the "substantial intellectual barriers" to success involves the development of a new model of science, one which enables the appropriate integration of disciplines that are fragmented, and which moves us beyond outmoded, reductionist assumptions. They suggest that hierarchical, systems theory can provide the needed framework of integration, and they call for work in the formulation of this systems theoretic alternative.

Embodied within the claims of the convergence advocates is a notion of science and the history of science. There are three distinct components: (1) that there is an old approach to science and engineering, in which knowledge is fragmented, pure and applied domains are distinct, and a reductionist approach is taken to the relation between disciplines; (2) that new research and tools in science, especially those associated with nano-scale science and technology, lead to a convergence of disciplines, a holistic approach to knowledge, and a more intimate intertwining of fundamental science and engineering; and (3) that hierarchical, systems theory can provide the framework for the integrated paradigm needed for this new science.

Many scientists and philosophers of scientists – including several contributors to this volume – are skeptical about each of these claims. Regarding the first claim, there is an interesting split between scientists and philosophers of science, with the former still having much confidence in reductionist approaches to knowledge and the latter believing that a full reductionism never characterized the theory or practice of any science, and thus that it is a myth that distracts one from a genuine history of any scientific development. In either case, there is a skepticism about the claim that we are moving away from such a reductionism. Regarding the second claim, both scientists and philosophers of science are skeptical about the uniqueness of the nano-scale. "Nano-" is seen as a ruse, drawing on the hype associated with visionaries such as Drexler, in order to get increased funding for what are otherwise very conventional projects. And regarding the third claim, there is a belief that no new notion of science is needed – whether based on systems theory or any other theory – because science never draws on such general notions for its practice anyway. Instead of such an overly general and unhelpful notion of the scientific enterprise, we should look at what is actually taking place within the disciplines, at the boundaries between the disciplines, and in the trading zones where knowledge and technology are produced.

Such nano-skeptics are likely to read the NBIC convergence claims as examples of rhetoric, whose sole purpose is to elevate otherwise conventional practices above peer-efforts, and thus to obtain higher levels of funding and prestige. Rather than give credence to the three claims outlined above, the skeptics shift the focus to the advocacy of human enhancement, seeing there the revolutionary program. Further, many are suspicious of that program. An overview of NBIC convergence claims and efforts thus shifts into a social/political criticism of the implicit ideology.

While there is undoubtedly a need for a more sustained analysis of the enhancement efforts, and there is also some truth in the nano-skeptic's analysis, I also believe that core considerations are either overlooked or misrepresented. Further, I think that the claims of Roco and others about the older approach to science, the newness of nano-, and the value of systems theory are all defendable. I will thus provide a reconstruction of the three claims, attempting to specify the content at issue, and also defend these claims in their reconstructed form. I will also suggest there are opportunities for establishing a rich dialogue between the sciences and humanities, which are directly intertwined with the claims that are at issue.

1. Some Preliminary Distinctions

In order to defend the NBIC claims about science, we need to distinguish between what scientists actually do and how they conceptualize what they are doing. While it is true that scientists never had, or could have, a simple hierarchy of disciplines, independence of pure and applied considerations, and so on, this does not mean the reductionist model didn't guide the way scientists conceptualized their own activity, reported their data, etc. In other words, when I give content to the so-called older approach to science – the reductionist model – I am not suggesting that science used to be like that and now it is different.

The reductionist model served a heuristic function for the scientist in conceptualizing his or her own activity. When Roco and others say we need a new approach to science and engineering, I will thus interpret them as saying we need a new model of the general activity of science – that something has changed such that the reductionist model no longer can serve its heuristic role. I will then specify the content of nano-scale work that is unique and that demands an alternative conceptualization.

Some will ask why a general model of science is needed at all. What is the heuristic value of such a model? To answer this, we need to distinguish between the different ways that scientists and philosophers use models. Modeling is obviously a major focus in current science studies. The focus is usually on the way scientists use models. Here a model is of whatever the scientist studies, and philosophers ask how such models are constructed, what they denote, how they are modified, and so on.

When philosophers consider how scientists use models they are modeling the modeling activity of the scientists. The domain is science itself, and the philosopher of science seeks to understand this in ways that are similar to how scientists understand their domain, whatever that may be. Such meta-models – namely, the philosopher's model of the activity of science – incorporates within it an account of the first level of modeling.

In order to appropriately interpret the claims of NBIC advocates, we must see that both the scientist and the philosopher engage in meta-modeling, but the function of their meta-models is different. For the scientist, the meta-model serves as a heuristic for the development of their models, while the philosopher is more directly concerned with meta-models that are isomorphic to the scientist's actual activity. Different criteria must thus be used in judging the diverse meta-models, and, given the alternative projects, competing accounts are fully compatible. In fact, the divide between scientists and those in science studies is partly a reflection of the diverse criteria they use for assessing their meta-models.

In what follows, I consider the notions of science that might inform the understanding and organizing activity of those involved in nano-scale science and technology and the broader NBIC convergence efforts. However, I will suggest that the systems theoretic alternative advocated by the scientists offers opportunity for consilience with meta-models advocated by philosophers, and, to this extent, there is a move from a meta-model that is less appropriate (in the philosophy of science sense) to one that is more appropriate.

Advocates of the NBIC convergence are convinced that a new view of science and engineering is needed. To assess whether this is the case and why, it is first necessary to consider the old view of science, and why it is inadequate. To this end, I now review the old meta-model, which involves a classical account of reduction, dualism, and linear causal relations. While this traditional understanding of science is generally rejected by scientists working in areas such as quantum theory and complexity, the reductionist program still characterizes the view of many other scientists (Wilson 1998). And it has been a valuable meta-model for the scientist – not because it is "true", but because it has served as a useful heuristic for organizing the activity of science. (To this extent it is analogous to a frictionless surface; *i.e.*, helpful for highlighting certain features valuable in analysis, but only of use as a first approximation.)

After my initial survey of the project of reduction, characteristics of nano-scale science and technology will be considered. Through this review, it will become clear that the assumptions about reduction no longer serve as a useful heuristic, since they contradict core features of this new science. A new view of science and engineering is indeed needed. However, the alternative cannot be a simple rejection of the reductionist project. Instead, features of reduction must be taken together with a more holistic analysis that accounts for irreducible complexity and fosters interconnections between the multiple scales and levels of disciplinary interaction. (As Roco puts it, we need an integration of left-brain reductionism with right-brain assembling views, 2002, pp. 73-74.) Instead of an either/or between reduction and holism, we need a both/and. Systems theory can provide the needed framework for this integration.

2. The Old View of Science: the Grand Project of Reduction and Unification

Scientists generally do not spend much time reflecting on the nature of the scientific enterprise itself; or, if this puts it too strongly, they at least do not worry about the nature of science in the way a philosopher would. Generally, they do not need to. Consider, for example, the activity of a molecular biologist. She can happily work on understanding a given protein and its function, simultaneously probing multiple levels of explanation, while being completely oblivious to the broader debate on holism vs. reduction in biology, or on the nature of the biological sciences more generally. Sometimes a logic of function unique to biology is presupposed, sometimes not. And it does not matter, since everything is on the way and interim. Slowly different things jump together, diverse domains of investigation converge, and the sense of being on the right track is clear. It all seems to work. So why spend the time reflecting on the nature and character of this endeavor?

While most scientists spend little time reflecting on the nature of science, this does not mean they do not generally have a view on the matter. In fact, as I outline below, scientists often espouse a classical, nineteenth century view of their enterprise. This involves the assumption that science follows a method that controls for bias and enables one to get at the objective world, and that the world is, in the end, composed of tiny parts, which are assembled to give the full array of complexity we see in the world. Higher levels of complexity are explained by breaking them into lower levels, and then showing how the higher levels can be built up from the lower ones. I will call this the project of a grand reduction. Whether or not a philosophy can be sustained that consistently upholds the notions of "objectivity", "scientific method", or "reduction" is not usually of concern to the scientist.

Captivated by the ideal of such a science, earlier philosophers of science attempted to reconstruct this project and its assumptions on a more rigorous foundation. (There are many different attempts at such reconstruction, ranging from the mechanical materialists of the 1850s-1880s to the logical positivists in the first half of the twentieth century.) While philosophy of science in the latter part of the twentieth century can be regarded as the breakdown of nearly all features of this project of reconstruction, many scientists still hold to such an ideal, highlighting an interesting tension between scientists and philosophers of science. (I will return to this contrast later, when we consider the relation between science and the humanities, and how systems theory makes possible a convergence of perspectives.) In presenting the older ideal, I will merge what might be considered "common sense" among many scientists (Popper 1979) with some of the features of the earlier philosophical reconstruction (Suppe 1977), in order to give a fuller picture of what the project of reduction entails.

When leaders of the NBIC convergence call for a new view of science and engineering, it seems clear that they regard the features of the grand reduction as the old view (Roco 2002). In summarizing this old view, I highlight four areas which will be challenged – or should I say "augmented" – by nano-scale science and technology, and a systems theoretic framework for that science. These four areas concern the hierarchy of the sciences, a complementary understanding of the nature and method of scientific investigation, a particular view of causality, and a set way of relating pure and applied sciences. Perhaps the most prominent recent statement of these features has been provided by E.O. Wilson (1998). I follow his formulation in much of my account. The project of the grand reduction can thus be understood as follows.

2.1 The Hierarchy of the Sciences and the Hierarchy of Nature

Advances in science have come by analysis. Wholes are broken into parts, which are understood with increased clarity, first in terms of a differential system of the whole and then in terms of an independent understanding of each part. Parts then become new wholes and the process of analysis continues ever downward. Worlds within worlds are discovered. With this tunneling, the universe is ever divided. Disciplinary fragmentation is partly a reflection of the success of this process.

Organizing the fragmented landscape has been an established hierarchy of disciplines. Physics owns the base. Chemistry builds on physics, biology on both, and the human sciences (psychology, sociology, economics) build upon the biological. With this hierarchy comes a broader vision of reassembling the scattered pieces. Radiating upward and outward from the subatomic particles of the physicist are the elements, compounds, and molecules of the chemist, and from there the macromolecular constituents of cells, tissue, organs, organ systems, and upward to the organisms and the psychological and social organization of these organisms. So nature emanates outward: ecosystems, earth systems, solar system, and so on, all the way to the cosmos. Similarly, there is a radiation outward in time, from the femtosecond vibrations at the subatomic level outward to the evolution of life and the cosmos itself. The hierarchy of scientific disciplines thus reflects the hierarchy of nature.

While these hierarchies are acknowledged by all, what characterizes the grand project of reduction is the belief that the higher level wholes can be fully understood in terms of their constituent parts; that they are no more than that sum. The goal of each science is then to provide the needed synthesis, reconstructing in the intellectual domain of science that pattern by which the whole is assembled chink by chink from its base elements in the natural world. Scientific knowledge is thus a mirror of nature, reconstructing in its theoretical models a pattern that is isomorphic with the natural order. And, most significantly for the project of reduction, the reconstruction proceeds upward and outward from the simplest components. Thus physics, concerned with the most fundamental aspects of the world, is not dependent on any of the other sciences. Chemistry, however, depends on physics, but not on the sciences above it in the hierarchy. So each higher level is independent from those above it, but dependent on those below it. There is thus an asymmetrical relation of dependence among the sciences. All higher levels are *in principle* reducible to the core terms found in the lower ones. If they are not yet *in fact* reducible, that simply points to the work that yet needs to be done within the sciences. Ultimately, all scientific knowledge is reducible to the principles of physics (Wilson 1998, p. 60). (Sometimes it is said that "all science is reducible to physics *and chemistry*", but on this account chemistry must in the end be reducible to physics, *i.e.*, to a knowledge of fundamental forces, subatomic particles and their interactions, etc.)

2.2 The Nature of Science and its Method

Complementing the hierarchy of nature and the sciences is a specific conceptualization of the scientific method. The scientist comes as a neutral observer, without any interests or values that might distort what is perceived and understood (Martin 1997). In order to assure this neutrality, a form of investigation is advanced, which builds in checks against bias. These checks are integral to the distinction between being objective and subjective. Objectivity is understood in a double sense: (a) that which is independent of the subject and characterizing the world independent of the observer, and also (b) that stance of the scientist that enables her or him to get at the world of nature as it is, rather than as the scientist wants it to be. There is thus a dualism between object (of investigation) and subject (who investigates); between objectivity (a neutral, open stance toward understanding nature as it is in itself) and subjectivity (an interested, and thus biased approach to investigation); and between fact (characterizing nature) and value (characterizing the subject).

The scientific method involves an empirical stance, and structures investigation so that simple causal relations can be isolated. First in the process of study is the reformulation of a poorly structured problem or question into a well structured one. This involves framing questions in such a way that experiment can answer them. Preliminary data serves as the basis for the formulation of a hypothesis, which is then tested by a controlled trial. "Data" is linked to simple observables (the pure empirical moment); namely, that "information of sense" which is uninfected by the interests, ideology, or values of the scientist (following Ernst Mach, this was the ideal for the positivist; Suppe 1977). The test of whether something constitutes such an "observable" is intersubjectivity: will all similarly situated individuals see this in the same way, regardless of their broader commitments? Just as the world is constructed from simple parts, so too is knowledge. The data of sense is organized by mathematical/logical rules to provide empirical generalizations; namely, laws. Multiple empirical laws are themselves grouped, yielding higher level generalizations. At the broadest level, foundational principles or axioms are formulated that account for the content given in the empirical generalizations. Through these higher level generalizations and theories, otherwise disconnected domains jump together or converge. The classic example of this is found in the merging of terrestrial and celestial mechanics; through Newton's three laws, the empirical laws of Galileo (terrestrial mechanics), and Kepler & Brahe (celestial mechanics) merge.

2.3 Causality, Explanation, and the Determinate World

Embodied within the classical notions of the scientific method are certain assumptions about causality and the character of the natural world (Weiss 1971). Every effect has a cause. To "explain" something, *e.g.*, some natural state or event, involves elucidating its necessary and sufficient conditions. Certain laws capture causal relations, so the explanation involves bringing the state/event to be explained under one of these "covering laws".

Ultimately, higher level phenomena are to be explained in terms of lower level components and their interactions. Lower level interactions, in turn, can be understood in terms of part-part relations; in other words, the wholes can be explained in terms of part functions, each of which can be isolated and sufficiently explained in its own terms. This capacity to discretely consider each component and its interactions is itself intertwined with the controlled experiment integral to scientific method. One can isolate the variable of interest, control for all else, and then discover the causal relation between this variable and others of interest. Explanation is thus linked to elucidating the "mechanism" involved.

A good example of the reduction can be found in biology, where, as Watson *et al.* (1992) note: "By now there exists an almost total consensus of informed minds that the essence of life can be explained by the same laws of physics and chemistry that have helped us understand, for example, why apples fall to the ground and why the moon does not..." Or, put in a more formal way, the reductionist position in biology can be defined as affirming that all aspects of biology can be defined in terms of an underlying mechanism. "Mechanism may now be defined as the view that every event E, which is describable as a biological event, is numerically the same as the set of events E_1 , E_2 , ..., E_n, in which each E_i exemplifies no laws that are not also exemplified in nonbiological systems ..." (Bechner 1967). The same is true for psychology, sociology, etc.: all phenomena can be broken into discrete parts and linear causal relations between these parts, which, in turn, can be taken as explaining (through the elucidation of mechanisms) what happens at the higher level.

2.4 The Relation between Pure and Applied Domains

The distinction between pure and applied science is a corollary of the dualism between fact and value. Pure science simply describes the world as it is, independent of the knower. "An applied science, by contrast, seeks to realize certain ends, and it draws on the pure sciences for the knowledge base and skills necessary to accomplish this" (Hempel 1960). Thus, for example, chemical engineering applies the concepts found in chemistry to synthesize desired products (often on a large scale); medicine applies knowledge of physics, chemistry and biology to the treatment of disease. In each case, the "basic sciences" (a term from medical education, characterizing the scientific foundations of practice, primarily learned in the first two years of medical school) enable one to understand the causal interactions of basic elements. The "application" of this knowledge in engineering or medicine involves an intervention in this causal sequence, or a construction of alternative conditions, for the purpose of advancing interests that lie outside of the science itself.

While "science" proper – *i.e.*, the "pure" activity – is independent from the diverse interests and values of individuals and society (at least in the content of its knowledge), their application presupposes such values. People want to accomplish things within the world. They have goals. These can be pursued in an ad hoc manner, or one can use the means-end reasoning of the scientist. The applied sciences are "mixed", in that they combine the extra-scientific ends/values with the capacity to causally intervene that arises from a knowledge of the world as it naturally is.

3. The Holism vs. Reduction Debate

Today all – or nearly all – philosophers of science would recognize each of these four points of the grand project of reduction as highly contentious and problematic. Scarcely a single philosopher would embrace this project in its classical form, and much of current philosophy traces the demise of the "Received View" of science, which was an attempt to formulate the grand reduction in rigorous terms (Klemke *et al.* 1988, Curd & Cover 1998). Despite this, however, many – perhaps even most – scientists still work with such assumptions about the nature of science (Wilson 1998). When scientists attempt to formulate in general terms the character of the scientific enterprise, they highlight exactly the core features of the grand reduction outlined above, and they contrast this with "vitalist", "metaphysical", or "religious" views that are taken as non-scientific.

It is worthwhile to explore these differences between philosophers of science and scientists, since the differences reflect a broader gulf between the sciences and humanities more generally. The isolation between the "science studies" of humanists (such as historians, sociologists and philosophers) and the activity of scientists themselves can thus be taken as an instance of this broader problem of fragmentation, providing an interesting lens on how diverse goals and methods of investigation lead to barriers in communication.

The divide between science and the humanities is more than just an academic dispute. Behind it lies a broader dispute about the role of science within the world. This is especially apparent in larger ethical and social disputes about certain areas of science and technology; for example, regarding genetically modified foods or nuclear power (Pool 1997). Generally, we address such ethical issues in the language of the humanities; namely, in the language of our cultural, literary, philosophical, and religious perspectives, all of which are holist in import. Because scientists (and much of the public) view science in reductionist terms, there is a bifurcation between the world of science and the world of ethics, as if "doing science" is completely different from "doing ethics". (This bifurcation reflects the reductionist distinctions between facts and values, and between pure and applied science.) Social and ethical reflection is thus seen as coming from outside science, and it often focuses upon constraints or regulation of the activity of science. This can further reinforce an antagonistic relation between the two domains, since scientists generally do not want to be thus constrained. However, at the same time, it is through science that we increasingly understand ourselves and our role within the world. The reductionist vs. holist controversy thus reflects a broader schizophrenia in our understanding of ourselves and our own activity.

When the leaders of NBIC convergence suggest that we need a new view of science, this can be taken as a challenge not just to the sciences, calling for a more sustained reflection on the nature of science, but also as a challenge to the humanities, and, more specifically, to the traditional gulf between the humanities and the sciences. In fact, NBIC leaders point in this direction when they suggest that there is a "trend towards unifying knowledge by combining natural sciences, social sciences, and humanities" (Roco & Bainbridge 2002, p. 11). If the scientists themselves come to appreciate the limits of reduction and explore alternative conceptualizations of the activity of science – something that is required by the very nature of the developing sciences – then this provides opportunities for convergence with notions of science found among philosophers, historians, and sociologists of science. This provides a unique opportunity for bridging the two cultures divide!

Claims to move beyond reduction should, however, be formulated in a careful way. A challenge to the grand project of reduction does not mean that one has to go to the opposite extreme. Older affirmations of holism were just as fragmenting as affirmations of reduction, since holists claimed a radical segregation of the disciplines, such that they are isolated by their logics from convergence/consilience. Put simply, it is time to move beyond the traditional opposition between the task of reduction and the interest in holism, emergence, and whole-part/top-down reasoning. Rather than either/or we now need a both/and approach. (I will elaborate more on this later.)

4. Modern Science Reframes the Debate: the Nano-revolution

Even though the project of the grand reduction did not and does not reflect the realities of scientific investigation (here I speak as a philosopher of science, and reveal my own bias), it has nevertheless provided a helpful model for structuring scientific investigation and for reporting the results of research. In other words, the grand reduction has historically served as a valuable heuristic, providing useful guidance to scientists who have been engaged in research. (Here the analogy is to a frictionless surface – useful as a heuristic, and providing a first approximation.) However, this model, which has for so long provided helpful guidance, is no longer helpful. Assumptions associated with the project of reduction now inhibit needed developments in science, engineering, and the humanities. In order to appreciate why a new account of the science and engineering is needed, I now consider the features of nanoscale science and technology (representing recent developments in science), showing why the older account of science no longer is helpful.

Many aspects of modern science have already challenged the grand project of reduction (Gibbons *et al.* 1994). One does not need to go to the nano-revolution to find these. To give just two prominent examples, 20th century developments in physics (esp. associated with quantum theory) already challenged older notions of causality and determinism, and with these, assumptions about method, the objectivity/subjectivity divide, and many other aspects of the grand reduction (Herbert 1985). Similarly, more recent work on chaos and complexity challenged the capacity to explain the world in terms of linear, causal interactions and to carry out the broader project of reduction (Waldrop 1992). Higher levels are now regarded as irreducible, leading to problems of emergence that cannot be resolved in traditional terms. However, these challenges – and many similar ones – are often taken in isolation, separated from one another, and understood as configuring localizable areas of crisis, but not undermining the whole project of reduction. Thus, for example, one could concede that quantum logics are strange, resisting standard accounts of the nature and activity of science, but such strangeness characterizes the world of the super small only. There is a different, more traditional logic for the classical domain, and, so the argument continues, it is within that domain that the project of reduction is still advancing (Wilson 1998).

What characterizes the nano-domain (and also some other emergent domains of modern science and technology; Gibbons *et al.* 1994) is that the various areas that are taken in isolation now converge, requiring a rethinking of the nature and activity of science. Within nanoscale science and technology this is seen in the following areas:

(1) Bridging quantum and classical domains

The process of analysis involves breaking wholes into their components. Synthesis entails building the wholes back up from their constituent parts. The grand project of reduction postulated that as one moves downward in scale, there is a general continuity in the logic of interaction between wholes and parts. However, as one approaches the bottom end of the nano-region, there is a shift to a quantum domain where the logic of explanation is radically altered. There is thus a floor to the classical domain; a discontinuity exists between it and the quantum level. What characterizes the nano-region is that one must bridge the quantum and classical. As Michael Roukes notes, "[m]atter at this mesoscale is often awkward to explore. It contains too many atoms to be easily understood by the straightforward application of quantum mechanics (although the fundamental laws still apply). Yet these systems are not so large as to be completely free of quantum effects; thus, they do not simply obey the classical physics governing the macroworld. It is precisely in this intermediate domain, the mesoworld, that unforeseen properties of collective systems emerge" (Roukes 2003, p. 93). The assumptions of the grand project of reduction do not help the nano-scientist come to terms with this strange middle world. Here the metaphor is one of "bridging" not "reduction".

(2) Merging bottom-up and top-down approaches

Two general approaches to fabrication are found within the nano-world: top-down and bottom-up. The first attempts to further refine and miniaturize methods already used in the micro world – methods such as lithography. The second seeks to build complex items up from the basic components, eventually leading to complex forms of self-assembly which mimic what takes place in the natural world. Within the nano-arena, these methods converge, and there is no clear preference in method (Venneri *et al.* 2002). At present, top-down approaches seem to have the edge in practicality, while bottom-up approaches hold greater promise for eventually realizing the broader ideals of nano-tech. However, both approaches will require more than a simple extension from the higher (in top-down) or lower (in bottom-up) domains. New "laws" will emerge for the nano-region. Here the standard hierarchies of explanation that characterize the grand project of reduction no longer apply.

(3) The symmetrical integration of physics, chemistry, and biology

Within nano-science, physics, chemistry, and biology are no longer related in the hierarchical, asymmetrical relation of dependence that characterizes the grand reduction. And these disciplines are not neatly associated with various scales (in fact, they never were). Rather, cutting-edge work in each discipline leads them to converge, and each informs the other. Yes, biology looks to physics and chemistry. However, the physicist and chemist also look to the natural self-assembly found in biology to better understand bottom-up nano-science

(Ball 2002). This is not just in the more "practical" technological endeavors, but in fundamental science, as well.

(4) Blurring the lines between pure and applied domains

If one views Feynman's famous lecture, "There's Plenty of Room at the Bottom" (Feynman, 1959), as a defining moment of nano-science, identifying core ideals, then it is clear from the beginning that older divisions between "basic science" and "engineering" are no longer applicable. The field was, in fact, defined by an interest in miniaturizing technologies already available; *i.e.*, in terms of engineering goals. The capacity to accomplish this was linked to new imaging technologies, which would enable us to "see" into the nano-realm; *i.e.*, to the results of the engineers endeavor. However, it is also clear that fundamental science is needed, and that, in fact, this realm promises to open up core areas of physics, chemistry, and biology to new forms of investigation. Rather than a simple hierarchy between basic and applied science, the nano-realm points to an iterative relation between them, with a continual blurring of the boundaries. Rather than a clear line, there is a continuum.

This iterative relation between science and engineering has another, significant implication: the goals that characterize the activity of the engineer reach into the basic sciences themselves, linking the focus and core features of analysis to the values and interests of the scientists and the broader community that funds them. This, of course, does not mean that anything goes, as if laws of the nano-world are created by the scientists. They are, indeed, discovered – for example, laws of self-assembly, or the quantum character of electrical or thermal conductivity – but the discovery is framed by the scientist's interest in micro-electronics or in designing nano-machines. Thus certain features of the nano-world come into view, and the "laws" are as much governed by the aims of the engineer as they are by the meso-nature of the nano-world.

Taken as a whole, these and other features of nano-scale science and technology are so alien to the project of reduction that a new account of science and engineering is needed. An account is needed that can (1) support discontinuities as well as continuities across scale, (2) involves both top-down/whole-part as well as bottom-up/part-whole logics, (3) bridges disciplines and opens symmetrical lines of communication between them, and (4) sustains the iterative relation and blurred boundaries between fundamental science and engineering. The nature and activity of science is itself complex, and we need a model that can come to terms with such complexity.

5. The Systems Theoretic Alternative

The systems concept has a long history, which we cannot explore here. There are also many, intertwined meanings to "system". However, for our purposes it is enough to highlight one aspect of this history and one core meaning to the systems concept.

The "systems" concept arose as an alternative to the contrast between mechanism in biology, on one side, and the vitalist impulse, on the other (von Bertalanffy 1952, 1968). This is the historically important context. (Another important historical origin is associated with attempts to formulate in logical/mathematical terms an idealized, abstract language for understanding logical operations. This work provided some of the logical and mathematical tools that are now used by systems theorists and applied to many domains in the empirical sciences (Henkin 1967). Here I highlight the biological debate, and I cite figures like von Bertalanffy and Weiss, because of the value of their ideas in understanding human enhancement, the stated goal of NBIC convergence. A fuller discussion of systems theory would necessarily involve a discussion of the formal tools of analysis, as well.)

Systems theory involves an attempt to transcend and encompass the two sides in the reduction vs. holism debate (this is central to its meaning, see Weiss 1977). On the side of the mechanist, the systems theorist affirms that many aspects of biological systems are subject to part-to-whole explanatory accounts, and that research should not postulate an isolated biological domain, insulated from the advances in physics and chemistry. Such isolation, advocated in the name of unique biological laws, only inhibits research in all domains. However, on the side of the holist, systems theorists claim that the whole often involves an irreducible priority in explanation, and that there are aspects of the system that could not be accounted for in terms of the sum of the components that make up that system (a variant of the many-body problem in physics.) Today, this holist argument is also closely wed to discussions of "complexity", with the recognition that alternative forms of analysis are required for complex systems.

The core systems concept is well summarized by the noted developmental biologist, Paul Weiss:

> First, what is it [a system] not? It is not a haphazard compilation of items nor, at the other extreme, a complex of rigidly linked pieces or events ... for in either of those cases, the complexion of the total unit could still be predicted unequivocally from the information about its constituent parts, pieced together. In a system, we are faced with the opposite property, that is to say, the state of a whole must be known in order to understand the coordination of the collective behavior of its parts; or if one prefers to objectivize this proposition, one can express it in terms of 'control' of the components by their collective state. (Weiss 1971, p. 13)

Once this basic idea is accepted, additional lines of investigation are opened up and legitimized in science, which cannot be sustained under reductionist assumptions.

First, complementing part-to-whole explanations, there are also whole-to-part explanations necessitated by the complexity of higher levels, and by the way higher level syntheses (the wholes) function in regulating the parts. In certain areas, such whole-to-part reasoning is well recognized; for example, in ecology or meteorology. By extending this systems concept more generally, however, one has a basis for integrating traditional part-to-whole explanatory accounts with higher level explanations. Some domains of investigation (such as an ecosystem ... or, perhaps, a cell ... or perhaps even certain properties of the mesorealm like quantum conductivity) need to be analyzed in their own terms, without a view to radical reduction. While reduction plays a role in broader analysis, there are also emergent problems – such as the equilibrium of an ecosystem – which cannot be accounted for in terms of the sum of lower level parts and processes.

Second, with the notion of a system comes the development of new, often iterative methods, which structure knowledge in terms of converging (or diverging) lines of investigation, and which transcend purely deductive or inductive approaches. Often there are iterative relations between experimentation and theory, or between pure and applied considerations, and one might never be able to completely account for one side of the iteration in terms of the other; for example, one might never be able to derive all results of experiment from background theoretical considerations. Scientific method is now seen as more complex than any formal accounts of the tools of analysis would imply.

Third, systems theorists are generally more self-aware regarding their role as scientists in the investigation, and the degree to which the "parts" and "causal line of influence" explored in science reflect the interests and choices of the investigators involved. Since interests and values play a role in even the most fundamental science, there is only a relative (but still valuable) distinction between pure and applied domains. Scientists need to see themselves as part of a broader natural system, and their knowledge arises from, and leads to, interactions with the systems that they study. This can be taken as a higher level generalization of the entanglement already recognized within quantum theory when one attempts to measure, and thus take stock of, the smallest objects of investigation. The very attempt to know involves a perturbation of the system known, and this effect needs to be accounted for by the scientist.

These features, integral to systems theory and implied by the basic system concept, support the features of science that are integral to nanoscience, which we identified in the previous section. Systems theory provides a framework that can account for the insights of the grand reduction, while augmenting these insights with additional forms of analysis that are necessary for the higher level, interdisciplinary investigation that is necessary. Even more than this, such a theory enables us to incorporate ethical considerations – such as an interest in the appropriate end of an intervention – in such a way that these considerations are continuous with the broader framework of scientific analysis. There is thus a convergence between the meta-models of the scientist, the meta-model of the philosopher of science, and the self-understanding of those involved in reflection on the human condition generally. Such a convergence of science and the humanities is valuable in itself, and it is vital if we are to appropriately guide NBIC convergence for human enhancement.

Notes

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