A Second Metamorphosis of Science: A Second View

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Outline:

1. **Introduction:** The Three Components of Science; (I) Scientific information (II) Scientific knowledge (understanding), (III) Concepts unifying knowledge in all physical sciences.

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3. **"Objective" and "Subjective" Aspects of the Components of Science**

Initial Phases of the Second Metamorphosis of Science:

4. **Transforming Component (I):** new sources of scientific information; Projections: new technical means for obtaining scientific information; the logically distinct character of information from different sources; Projections uncovering complex dynamic phenomena; some broad implications.

5. **Transforming Component (II):** Understanding based on the discovery of relationships between observables, concurrent and sequential; Understanding based on "associating" logically distinct forms of information from different sources of information; Generalizations and refinements of "scientific methods"; new technical features and complications.

[1] This working paper is an extension of "A First Look at the Second Metamorphosis of Science" (Santa Fe Institute Working Paper, 95-01-001; and CCSR Report, Beckman Institute), and based in part on the lecture "The Second Metamorphosis of Science", given at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria, on July 21, 1995. I am grateful to IIASA for the invitation to present these ideas within the context of the 1995 Tjalling Koopmans Distinguished Lecture Series, "Evolution and Complexity".

6. **The "Inward-Bound" and "Outward-Bound" Bifurcation within Physics:** Conflicting concepts of reductionism within Science; the metaphysics of faith vs. constructionism.

7. **Transforming Component (III):** The search for a technical "scaffolding meta-science"; constructionism and reductionism; varieties of hierarchies; the bilevel reduction-construction understanding of natural phenomena, based on interactions of "ensemble" variables in constrained environments.

1 Introduction: The Three Components of Science

The business of science is to develop new understandings of old and newly explored natural phenomena. During the past century we have seen an explosion in new understandings, to varying degrees in physics, chemistry, biology, astronomy, geology, areas of economics, psychology, and in a variety of social, ecological, and political contexts. All of this is pushing the frontiers of scientific exploration into ever more complex phenomena. While these developments are what science is supposed to be all about, there is a growing realization that more is happening (and needs to happen) within science than simply the development of isolated new theories.

We are being overwhelmed by massive amounts of information (facts) concerning more and more "complex phenomena", leading to such reactions as that by Philip W. Anderson, a Nobel Laureate in Physics, who wrote an article "Is Complexity Physics? Is It Science? What Is It?" [1]. Indeed, all this information about "complex phenomena" is not knowledge, in the sense of understanding. As Poincaré expressed it, "Facts do not speak". Thus the much-acclaimed development of the "information super-highway" can easily generate the "knowledge super-cemetery".

The process of acquiring a scientific understanding of complex natural phenomena requires a re-examination of the foundations of science. The foundational components of science, which have been used very successfully during the past three hundred years, have only been applied within a very limited realm of dynamics of inanimate matter. These foundations are already changing in basic technical respects, raising many new fundamental questions about the form of our knowledge, as well as the need for metaphysical (metascience) reassessments.

I believe that the only adequate approach to understanding these increasingly complex phenomena requires the recognition that Science itself needs (and indeed has begun) to evolve it foundations, in order to make it possible to have an understanding of at least some of the wondrous complicated phenomena around us. Because this involves a change in the basic structure (morphology) of Science, I choose to describe it as a "metamorphosis of Science".

It is useful to differentiate the activities comprising Science into three basic "components", which have different degrees of "objectivity" and "subjectivity". Delaying these issues until later, let me simply give this brief outline of what is involved in these three components:

I) The technical operations that are used to obtain "scientific information" ("facts", "observables") from various (presently three) sources. The scientific character of this information requires that these observables have a communal character, and can be recorded in some agreed associative symbolic manner.

II) The methods that are developed to turn this information into a consensual form of “scientific knowledge (understanding)” of specific physical phenomena. This requires the discovery of either concurrent or temporally-sequential correlations between a set of observables.

III) The generation of a metascientific (“metaphysical”) program by scientists, concerning how scientific information can realistically (and not just as a matter of philosophic “in principle” faith) be used to obtain a coherent, unified method of understanding of some broad category of our natural experiences.

By a metamorphosis of science, I mean that all of these basic components of science are fundamentally transformed into new structures. This is to be distinguished from the multiple “scientific revolutions” that are frequently referred to in connection with important new theories [2,3]. A metamorphosis refers to a fundamental change in the operational components that go into developing any new theory. In the following overview, I will indicate in what sense we are in the initial phases of such a metamorphosis of science - the full character of which will probably not be clear for at least a century, so this discussion can safely put forth any “reasonable” suggestion about this final transformation!

[1] P. W. Anderson, Physics Today, July 1991; and this reaction came despite his pioneering recognition of the basic changes occurring in Science, “More Is Different: broken symmetry and the nature of hierarchical structure of science”, Science 177, 392 (1972)

[2] I. B. Cohen, Revolution in Science (Belknap Press of Harvard Univ. Press, 1985)

[3] T. S. Kuhn, The Structure of Scientific Revolutions (Univ. of Chicago Press, 1970, sec. ed. enlarged)

2 The First Metamorphosis of Science

To clarify the meaning of a "metamorphosis of science", and to give a base line for the transformation that is beginning to take place in the second metamorphosis, I will sketch some of the technical and metaphysical components that were established by the first metamorphosis.

The period of time that I am referring to is roughly from 1570 to 1790. Those primarily responsible for the changes in the foundations of science were T. Brahe, J. Kepler, G. Galilei, R. Descartes, F. Bacon, I. Newton, G. W. Leibniz, L. Euler, and J. L. Lagrange. The earlier portion of this transition is frequently referred to as "The Scientific Revolution", but the concept of a revolution in science has taken on a variety of meanings [1], none of which correspond to the present concept of the evolutionary transformation of the basic components of Science, (I),(II),(III), briefly outlined in the section 1.

Prior to this period there were isolated studies of natural phenomena that would certainly be recognized today as being "scientific". The names of Archimedes and Pythagoras certainly come to mind. And, of course, among the most extensive observations and commentaries were those due to Aristotle, who effectively defined the field of biology until the middle of the 19th century [2]. In particular, Aristotle's systematic collection of biological information involved a basic component of Science, (I). However, as R. Thom noted in the middle of this century, this information alone can lead to his characterization: "Biology is a cemetery of facts." In more recent times we are in much the same stage of development in some areas of neurological studies of the brain. Thus the collection of facts does not imply that the science has yet advanced to include the activity (II) - namely developing some scientific understanding.

What is important to recognize is that Archimedes and Pythagoras each made a discovery about a general relationship (holding for an extensive class of systems) between several observable quantities. Their general relationships involved algebraic relationships between observables. Archimedes' famous "Eureka!" discovery concerned the reduction in weight of a body in water (his tub) and the weight of the displaced water. The Pythagorian story purports to relate the tones of vibrating fibers and the weights applied to produce their tension (which was reassessed and corrected by Galileo's father).

Regardless of the accuracy of these historical tales, the essential point is that a scientific form of knowledge (understanding) was appreciated by a select group of people - and this knowledge involved the discovery of relationships between observed quantities (a set of correlated observables). Relationships were also the focus of Eastern cultures [3], but not in the context of trying to find a general relationship for some class of natural phenomena. Thus, the discovery of relationships was (and still is) a primal form of scientific knowledge. It should also be noted that, in this earliest form, the relationships were of a concurrent character (at the same time). A significant aspect of the first metamorphosis of science was to extend this to sequential relationships.

With this brief background, let me outline the changes that occurred in these three basic components of Science during the first metamorphosis:

I) Changes in the technical sources for obtaining "scientific information"

In addition natural phenomena as a source of information, and the systematic collecting of facts from physical observations, as exemplified by Aristotle's biological observations, an entirely new source of "information" was introduced (and accepted in varying degrees) in the mathematics of calculus and ordinary differential equations, invented by Newton and Leibniz. This mathematics of differential equations is profoundly different in both form and conception from the mathematics expounded by Galileo - algebra and geometry.

Associated with this was the introduction of the time, t, as a mathematical variable - a new concept in mathematics, with many implications.

The development of methods of mathematical analysis, particularly by Euler, who has been called "the Mozart of mathematics". These methods focused on obtaining analytic solutions of the differential equations. This had a number of implications, which I will outline under (III).

The very interesting, and little noted, extension of planetary and particle dynamics to systems of fluids and field variables. These are described by partial differential equations, which were pioneered by Daniel Bernoulli and Leonard Euler. The variables of these equations are not generally related to simple "observables" - they are already a more generalized view of Nature.

The interesting historical fact that Leibniz founded the concept of symbolic (mathematical) logic, but failed to publish it, requiring its rediscovery some 150 years later - and a profound source of mathematical information [4].

II) New methods to develop scientific knowledge (understanding)

With the introduction a differential equations, particularly in connection with Newton's equations of motion, and gravitational forces, the concept of a "scientific method" was variously envisioned by Descartes and Bacon, and has had a jaded history ever since [5,6]. However, the basic new concept was that science needs to validate its "understanding" of some natural phenomenon by relating the physical observations to logical deductions, obtained from a related mathematical theory.

In a simplistic characterization, one form of the scientific method can be represented as in the following figure:

Natural Systems		Formal (Logical) Systems
Physical Observations	**————–>**	**Mathematical "Theories/Laws"**
Comparisons	**("encoding-decoding")**	**logical inferences**
physical deductions	**<————–**	**mathematical deductions (e.g., analytic solutions)**

It is through various circulations around this figure, involving many different types of actions, that one is attempting to define a "scientific method" for logically "validating" our understanding of some natural phenomenon. Thus the "related mathematical theory" often involve differential equations of some variables, which are somehow related to the physical observables. Moreover these equations are themselves expressions of sequential (not concurrent) relationships between observables at one time and "the next instant" of time - the so-called infinitesimal calculus. Hence another (mathematical) relationship had to be discovered to obtain these equations (sometimes referred to as an inductive process), even before the required logical deduction of the "scientific method" could be accomplished. Thus the scientific method really involves several distinct levels of understanding and suppositions - points which become more sharply focused in the second metamorphosis of science; in particular the nonlogical association of "encoding-decoding" different types of information.

III) The metaphysical impacts were numerous:

Here one could spend a great deal of time discussing the various facets of related philosophical changes that took place during this period, but I will simply emphasize a few points of particular interest:

- The concept of the natural laws of God, as applied to the moral aspects of human activities, became extended into the concept of God-given laws of Nature, which apply to non-moral and non-human phenomena. While there had been random illusions to such laws of Nature for centuries, this concept only became fully developed by Boyle and Newton, in connection with chemical and planetary systems [7,8,9].
- The power of mathematical reasoning had a great impact on the metaphysics of scientists, as expressed often by René Descartes. Bacon and Descartes were rather the Yin-Yang of the Scientific Method; Bacon emphasized the importance of physical experiments, whereas Descartes strongly supported the power of mathematical reasoning.
- Mathematics had a strong and pervasive appeal. It offered, after all, the power of unarguable logical deductions, arbitrarily precise answers, predictions valid for all times, and of course the great appeal of causal understanding.

- The unification of the previously separate realms of celestial and terrestrial phenomena, by Newton's theory of gravitation, not only gave impetus to the concept of God-given laws of nature, but also suggested the idea that there are indeed "universal laws", applicable to "everything", which has had a lasting impact to this day.

Before turning the to the details of the new technical aspects that are contributing to the initial phases of the second metamorphosis, I want to return briefly to the different contents of the three basic components of Science, outlined in section 1.

[1] J. B. Cohen, Revolution in Science (Harvard Univ. Press, 1985)

[2] J. A. Moore, Science as a Way of Knowing: the foundations of modern biology (Harvard Univ. Press, 1993)

[3] J. Needham, Science and Civilisation in China; Vol. 2, History of Scientific Thought. Section 13(f); correlative thinking and its significance; Tung Chung-Shu (Cambridge Univ. Press, 1956)

[4] B. Russell, "A History of Western Philosophy" p. 591ff (Simon & Schuster)

[5] H. H. Bauer, Scientific Literacy and the Myth of the Scientific Method (Univ. Illinois Press, 1992)

[6] J. Ziman, Reliable Knowledge: and exploration of the grounds for belief in science (Cambridge Univ. Press, 1991)

[7] J. Needham, Ibid., section 18(d): Stages in the Mesopotamian-European differentiation of natural law and laws of nature.

[8] T. E. Huff, The Rise of Early Modern Science: Islam, China, and the West (Cambridge Univ. Press, 1995)

[9] F. Staal, Concepts of science in Europe and Asia, Interdisciplinary Science Rev. 20, 7-19 (1995)

3 “Objective” and “Subjective” Aspects of the Components of Science

Before turning the to the technical details that contributed to the initial phases of the second metamorphosis, I want to return briefly to the basic components of Science, outlined in section 1, and point out an important distinction between two different attributes that contribute to portions of each of these components. These different attributes may fairly be referred to as “objective” and “subjective” in a well-defined sense. Of course not everybody will agree with this designation, but I think that it is at least a useful distinction, which can remove “philosophy” from some aspects of this analysis. So let me briefly outline these distinctions in parts of each component, (I), (II), and (III).

The various technical operations and methods used to obtain scientific information are largely objective in character. That is to say that they are widely used by all scientists, and most importantly the information obtained is communal in character - i.e., can be shared by all. These operations often involve instruments and measurements, or logical deductions from mathematical equations or from computer algorithms. In this communal sense at least, the component (I) of Science is entirely “objective” [1]. Of course the selections of what to observe and experiment on are unavoidably of a subjective (individual) character - Science, after all is inspired by human inventiveness! Nonetheless, even here, the selection must gain acceptance by a community of people before it becomes part of Science - so it again must have this communal sense of objectivity (there are obviously various time scales that can enter into this process, but that does not change this characterization). To emphasize this objective basis of the initiation of the second metamorphosis of science, these technical operations will be the focus of the next section.

The “subjective” attributes of parts of the scientific components is related to philosophical and metaphysical beliefs, or various social influences, generated within the community of scientists. The “scientific methods” of component (II) contains a mixture of such subjective aspects, as well as objective technical factors. Historically little attention has been paid to these technical factors, such as the “encoding-decoding” association in the “scientific method” outlined in the last section. This can be traced to the simplicity of the phenomena that was investigated - a situation that is dramatically changing, as will be detailed more in the next section. But it is essential to recognize that the component (II) contains both “objective” and “subjective” aspects, and these should not be muddied up under some “scientific method” characterization. This will make discussion of the transformation of the component (II) in the second metamorphosis much clearer, as will be discussed in section 5.

The component (III) has historically been dominated by philosophical and “metaphysical” beliefs, which have nearly always been treated in a subjective matter. However if we replace the ancient vision of “metaphysics” - the realm of philosophers - by a “metascience” which is properly defined for the use by scientists, then this component of Science will be transformed into one that is subject to significant objective constraints. Some of these are dictated by the character of scientific knowledge generated by the components (I) and (II), and others will be recognized in terms of the human capacity for comprehension. But even the "subjective" factors of (III), which will still tend to dominate this component of Science, will be transformed into more useful visions of explorations and unity of all fields in Science. This issues will be taken up in sections 6 and 7.

I think that it is very important to emphasize these issues, because the second metamorphosis of science has been initiated by technical, and largely objective, discoveries - and we should not muddy this up with philosophical considerations any sooner than we have to! So I now turn first to the development of new technical methods for obtaining scientific information, which is the genesis for the second metamorphosis of science.

[1] This sense of (scientific) objectivity is entirely different from the (philosophical) objectivity envisioned by K. R. Popper, Objective Knowledge (Oxford Univ. Press, 1979), pp. 108-9: "Knowledge in the objective sense is *knowledge without a knower*; It is *knowledge without a knowing subject*".

Initial Phases of The Second Metamorphosis of Science:

4 Transformations of Component (I):

new sources of scientific information; Projections: new technical means of obtaining scientific information from different sources; projections uncovering complex dynamic phenomena; broad implications

The second metamorphosis has been initiated by a number of new technical insights into the dynamics of complicated natural phenomena. The primal and most objective component of Science involves obtaining scientific information. The discussion of the issues in (I) will make it clear that this the second metamorphosis of Science was not initially driven by philosophical considerations, but rather by technical objective discoveries. This is important to recognize, so I will give an outline of at least some of these technical ideas, in order to have any real appreciation for what has occurred thus far in this second metamorphosis.

First of all, there has been a basic transformation in the sources of scientific information since the time of Newton. It is generally recognized (or will be!), that there are now three independent sources of scientific information:

NATURAL PHENOMENA (NP)

MATHEMATICAL MODELS (MM)

COMPUTER EXPLORATIONS (CE)

Hence a great transformation has occurred in the sources of scientific information, through the advent of the digital computer. To give the widest implication to this new source of information, I use the expression "explorations", implying no preset boundaries to the application of computers in the search for insight into any area of natural phenomena. Some details of these explorations will be discussed shortly. However, keep in mind that these are all simply sources of information, not information as such. We proceed now to see some of the changes in scientific information, obtained from the above triad of sources.

We can obtain some scientific information (facts, observables) from these sources, only to the degree that we develop technical methods that effectively "project out" some comprehensible form of information from a source- say, some "small/understandable" numbers, or some other symbolic representation (e.g., pictorial, sonic, etc.), which we can recognize and feel is appropriate to associate with "what is going" on in these sources. This is "scientific information" only if there is a consensus among scientists that this is an acceptable representation of some feature of what is going on in a source. This puts a major constraint on this type of information - an objective constraint.

So the technical problems of generating scientific information is to develop projections from these sources into "observables" related to these sources. Schematically we can represent these projections in the form:

		(projections)
Natural Phenomena (NP)	$\rightarrow$	**Physical Observables (PO)** **(instrumental/human associations)**
Mathematical Models (MM)	$\rightarrow$	**Mathematical Observables (MO)** **(logically deduced consequences)**
Computer Explorations (CE)	$\rightarrow$	**Computational Observables (CO)** **(comprehensible/communal** **compression of computer data)**

Now let me briefly outline some of these new technical methods of making projections and discoveries, as they apply to each of these sources:

(NP –> PO): Natural Phenomena to scientific physical observables

In the latter half of this century there has been a dramatic array of new methods to obtain physical observables from natural phenomena. What follows is only a few of these new methods:

** Computer data acquisition and analyses -

While the development of new experimental instruments is a continual feature of the evolution of science, it is clear that the digital computer has introduced a conceptually new form of instrumentation for obtaining information from natural phenomena. This is due to its ability to take a massive amount of information from any instrument that is monitoring a physical process, and to "compress" this information in any prescribed fashion, to yield some comprehensible observable. Numerous examples exist is such areas as high energy physics, meteorology, medicine, industry, astronomy, etc. To make use of this capabilities to its fullest, depends on the development of other instruments that can generate new information for computers to compress in yet more inventive fashions.

** Satellite instruments, yielding observables in: astronomy (Hubble telescope, COBE-cosmic background radiation), ecological studies, meteorology, geology, oceanography, human activities (military, migrations, farming, deforestation, etc..), weightless biological and physical processes, etc.

** Projections of processes in the brain: Electroencephalography (EEG); Positive Emission Tomography (PET), using radioactive labeling of blood, blood sugars, neurotransmitters (e.g., dopamine); Magnetic Resonance Imaging (functional MRI); Magnetoencephalography (MEG), using liquid helium superconductor sensors (Squids) to detect magnetic fields in the brain that are 10^{-9} the strength of the Earth's magnetic field, projects out 40 Hz waves that sweep the brain (binding process?)

** Microscopes: such as electron, and high-field intensity microscopes, capable of projecting information at atomic scales, and fluorescent microscopes.

** Holographic-generated laser pulses, yielding customized time-space fields for projecting information about complex structures

** Optical fibers that obtain information from many difficult areas, such as the interior of the functioning human body.

(MM –> MO) Mathematical Models to Mathematical "Observables" (deductions); New methods of making mathematical deductions; new holistic observables

Since the time of Newton, the primary concept of mathematical understanding from the differential equations of calculus involved obtaining analytic solutions of these equations - that is, general solutions, which are explicit functions of time (the new variable of mathematics). The dominance of analytic dynamics, was first epitomized by Lagrange's great works on the subject [1], and exemplified by the book by Whittaker at the turn of this century [2]. Lagrange was particularly proud of the fact that his book contained no geometric figures, whereas Newton's Principia contained no differential equations! The ability to obtain explicit analytic solutions ran into great difficulties, and various "perturbation methods" were developed. This tradition was carried into the quantum mechanics of this century, where such methods as the Born-Oppenheimer perturbation theory was developed, or simple "approximations" such as "Fermi's golden rule". In the time-independent dynamics of scattering theory, much more sophisticated methods, based on selections from "Feynman diagrams", were developed. However, within the field of time-dependent phenomena, all perturbation methods were the same as those developed in the last century. No rigorous method was devised for obtaining information from perturbations until the work of Kolmogorov-Arnold-Moser in the 1950s and 1960s.

Had these scientists been more aware of Poincaré's work on celestial mechanics in the 1890's [2,3], as was Brillouin [4], they would have learned that their perturbation methods failed to give general solutions. In the 1890's Poincaré, Bruns, and Painlevé, to name a few [see 2], proved a number of very restrictive theorems concerning the existence of perturbative solutions of conservative dynamic systems.

With the downfall of their most basic method for obtain deductive results (information) from their differential equations, the question naturally arose as to what could one do to at least supplement this method for obtaining mathematical information. An essential lesson that was learned here is:

Given some mathematical temporal-sequence relationship for some observables, described by a set of differential equations (or discrete-time difference equations), it does not follow that one can obtain any long-time information about the behavior of the dynamics of particular solutions generated by that system of equations.

So what is one to do? Fortunately they (and all succeeding scientists and mathematicians) had Poincaré to fall back on!

What Poincaré developed was a number of new concepts, which lie at the heart of much of our present understanding of the dynamics of complex systems. This understanding comes from entirely new ways of looking at dynamics - ways which have little to do with the historical focus on making predictions about specific situations. Rather the new insights are associated with various relational concepts; relationships between whole families of physical situations, how to characterize them, and how to study the ways they can totally change their character. Put another way, it is the new joint vision:

Dynamic Relationships *vis-a-vis* **Dynamic Causalities.**

I think that some appreciation of these new relational insights are very important in attempting to understand what the future transformation of Science will involve, so let me outline some of these ideas. For a more complete, but friendly introduction, see [5].

Mathematical equations involve so-called dynamic variables $x(t)$, $y(t)$, etc., which depend on the time, t. These variables are frequently simply symbolic representations of some physical observables in an experiment, or a simple observation. The equations prescribe how these variables change in time, depending on their present values. Now, rather than try to find the behavior of a particular situation, characterized by some (initial) condition, which specifies the values of the variables at some time, say $t = 0$, Poincaré consider the behavior of all of the solutions, by representing them in a "phase (or state) space".

This is best appreciated with a few pictures. Let me consider the case of only two dynamic variables, and call them $x_1(t)$ and $x_2(t)$. Then I make use of a representation invented by Descarte, involving two axes on which one keeps track of the value of one of these variables $-x_1(t)$ on one, and $x_2(t)$ on the other. At any instant of time the value of $x_1(t)$ and $x_2(t)$ specifies a point in this "phase space", and as time moves on, so does the point - sweeping out a curve, as shown in fig. 1

fig 1. periodic solution

What is shown here are three different solutions, and they all repeat their motion over and over on their individual curves ("orbits"). They are called periodic solutions, such as a swinging pendulum (where $x_1(t)$ represents the angle between the pendulum arm and the vertical, and $x_2(t)$ represents the rate of change of this angle (per second)).

Figure 2 shows a different type of system, in which the motion tends to the origin as the time increases. The origin in this case is called an "attractor", since all nearby solutions tend toward. This attractor is simply a point (a "fixed point" or stationary state of this system). Such attractors are very important in nature, because all of the structures you see around you are the consequence of some complicated form of attractor dynamics.

fig 2 stable focus

A second very important type of attractor is a periodic attractor. This is illustrated in Figure 3.

fig. 3 stable limit cycle

This attracting type of cyclic (periodic) motion is called a "limit cycle". It is a very important type of "autocatalytic" dynamics. It characterizes the dynamics of systems that are open to a flux of energy from-and-to their environments - such as our hearts, and many mechanical and electrical systems.

Thus, so far we have encountered the concepts: phase space; orbits in phase space; periodic orbits; fixed-point attractors; periodic attractors (limit cycles). None of these concepts explicitly involve the value of t; it is only the arrows on the orbits that indicate the direction of the motion as time increases. This is already very different from the focus of analytic solutions. What we have here are new global and holistic viewpoints about dynamics in systems.

Now the next concept is particularly beautiful, and very important for appreciating some new characterizations of complex systems. We note that in figure 1 that several different orbits have been drawn, and we can well imagine that there are many other cases (orbits) which are of the same character (periodic around the origin). In other words, we don't need to draw all of the orbits in order to characterize the general physical behavior of this system - namely that it will always behave periodically. A set of orbits that identifies a general characteristic of the physical system is called a "phase portrait" - rather like a family portrait identifying the "character" of a family.

Now consider the phase portrait in figure 4. It clearly also expresses the fact that this system behaves periodically, even if differently in details from the system in figure 1.

fig. 4 - wiggley periodicity

If figure 1 had been drawn on a rubber sheet, we could stretch it in a manner that would cause the orbits to look like those in figure 4. In other words, these two systems are equivalent when subjected to some "rubber-sheet geometry distortions". If two systems have this type of equivalence, they are said to be "topologically equivalent". Thus the limit cycle in figure 3 is not topologically equivalent to those in figure 1 and 4, because it can not be deformed on a rubber sheet into the latter figures. Similarly figure 2 is not topologically equivalent to any of the other systems. What this tells us is that a basic dynamic characteristic of the systems in figures 1, 2, and 3 have essential differences - and this a general property of the system, not simply of some particular situation. There is a qualitative difference between these systems.

A dynamic system may be represented by equations that contain parameters, which related to the influence of its environment ("exogenous variables", such as force fields, temperature, tax policies, etc.). If these parameters change, a system may change from one form of dynamics to another that is topologically distinct. If this happens, we say that it has undergone a “bifurcation” - which is clearly an important new (holistic and qualitative) perspective of the changes in systems.

Hence, with this phase space representation we can capture new relational (holistic) qualities of the general behavior of systems, in contrast to focusing exclusively on the predictive interests of the past. This is a very important transformation of the character of mathematical “observables” (deductions) - no longer being confined to the quantitative and causal features of particular situations.

Poincaré was the person who developed these concepts of topology into a field of mathematics, and applied them to the study of dynamic systems. Among his great inventions was the concept of a “Poincaré map”, which extracts only discrete-time information from the full dynamics of a system. This is illustrated in figure 5, where we see two different orbits that pierce a surface in the phase space, labeled S_o. One orbit is periodic motion, and intersects S_o only at one point, p_o. The second orbit is apparently not periodic (ultimately it might be),

fig 5. Poincaré map

piercing S_o at the two points x_1 and x_2. One says that the Poincaré map of this system's dynamics “maps” p_o into p_o, and x_0 into x_1 respectively. Remarkably, by discarding most of the dynamic information of the solution of a MM, one can deduce new holistic types of information about the motion.

Poincaré applied this method to a long-standing astronomical problem, concerning the behavior of three gravitationally attracting planets. Combining his map with other general features of such dynamics, Poincaré conjectured that there exists amazingly complicated holistic features in this dynamic system. This was particularly amazing, since planetary motion had always been seen as the hallmark of Newton's “clock-like” determinism. It wasn't until 1927 that the mathematician Birkhoff was able to prove Poincaré's conjecture [see, e.g., 3 and 5]. To give you some sense of this complexity, let me just paraphrase the Poincaré-Birkhoff result:

Poincaré-Birkhoff Theorem: In any small region of a periodic point (like p_o) on S_o, there are an infinite number of periodic points with different periods, and an uncountable number of nonperiodic solutions (i.e., points which never map back to themselves, as x_0 and x_1 might do, if that orbit closes in the future).

fig. 6 - Poincaré tangle

The complexity of this dynamics is only roughly suggested by figure 6, indicating some of the points on S_o that are produced by different solutions of the three-body MM. This is sometimes referred to as the "Poincaré tangle", for good reason! Note that, if you look in the region of any central "target" pattern, you will find this same complex structure all over again (just on a smaller scale). Thus it is an unimaginably complicate statement about the global behavior of what had been viewed as "Newton's clock" - the first indication of "chaotic" dynamics in our macroscopic world. This has profound implications about our use of mathematics to obtain scientific knowledge (understanding) of physical observables - to be discussed in section 5.

These results show that there has already been a profound transformation of obtaining information from MMs. Next we turn to the totally new source of information, digital computers.

(CE -> CO) Projections in computational mathematics, and the search for projections in abstract computer explorations.

There are two quite distinct categories of Computer Explorations. One can be called computational mathematics - forming the basis for a new technical journal, the Journal of Experimental Mathematics. This is an application of computers to "solve" mathematical equations or explore various mathematical issues. The former involves starting with mathematical equations, and writing some algorithm which is believed to accurately (in some sense) represent the differential equations (for example), after which one obtains special "solutions". The "observables" in these cases is often simply the outputs of the computer's representation of the variables of the original equations. And that's that. But not really, because there are many questions about how closely the computer output represents the true solution of the original mathematical equations (an example being the so-called "shadowing problem"). There are also various statistical (Monte Carlo) approaches to obtaining information about solutions of complex systems - all subject to many limitations and questions. There is also the use of computers to simply explore a very large number of well-specified situations - the first successful application being the "computer proof" of the famous four-color problems.

More relevant to the physical sciences is the use of computers to "solve" MM of physical significance. One of the earliest examples led to the discovery of the Fermi-Pasta-Ulam phenomena - an unexpected lack of irreversible behavior (a "little discovery": Fermi) [e.g., 5]- and the renowned discovery by Edward Lorenz of a "strange attractor" [6, 5]. A single trajectory of this system in the three-dimensional phase space is illustrated in figure 7. All dynamics in this phase space is "attracted" to this behavior. Two systems that are initially in very similar conditions (labeled 1 and 2 in the figure)

fig. 7 strange attractor

will ultimately behave very differently (this is known as "sensitivity to initial conditions"). In such systems it is not possible to make long-time predictions, because the initial state of any physical system is only known approximately (from the mathematical point of view). What is much less appreciated is that two systems that are initially in very different conditions, such as 3 and 4 in fig. 7, will become very similar for brief periods of time, only to rapidly separate - and this continues into the future. This combined complicated feature is one aspect of what is known as "mixing" in dynamics. It is again a holistic concept. The significance of Lorenz's discovery to computational knowledge will be discussed further in section 5.

Now all of these examples of computational mathematics can logically be disassociated from the use of MM within the physical sciences, if one takes the point of view that the algorithm stands in precisely as fundamental a position as any MM [7]. In this case, there is no question about the result of a CE being "close" to a MM - the computer program of the CE is simply the fundamental source of information. When it comes to some Monte Carlo implementation, the view can be taken that this is a projection method being applied to a fundamental source of information. It presumably has a significant statistical advantage over any particular solution, which gives it more of a holistic understanding of a system - but it also has significant limitations.

However there is a totally distinct group of "abstract" CE, which delve into the dynamics of the fantasy worlds of various programmers - each being a God of his own creation. The spectrum of these "abstract" CE that now exist is not possible to survey - it grows exponentially with every wild idea. Some of these CE are attempting to understand, or at least explore, dynamic phenomena in some of Nature's most complex systems - those that involve cognitive processes, and all of humanities often irrational behavior. A few of the more profound investigations along these lines are listed in [8].

The first of this breed of abstract exploration was due to Stanislow Ulam, which is now called cellular automata. Ulam suggested that von Neumann might find this useful in developing his ideas about self-reproducing automata [9]. Since then this area of research has grown greatly [10], but one may feel that it has led to only very limited amounts of understanding.

The problem, which is systemic to abstract CE, is that it is very difficult to find "meaningful" (i.e., correlatable) sets of projected (compressed) observables. You can look at the computer screen and be amused and amazed at what you see, but what precisely is connected with what? These "whats" need to be comprehensible, and not just some nice dancing patterns. In that projection to comprehensibles lies many challenges.

However a CE is significantly different from just looking out the window at an approaching storm, or blowing leaves, and so on. The computer, after all, has been programmed in a known way, and can be changed in any desired fashion to "see" the resulting effects (but to understand?). Moreover it puts out its data in binary forms, so it has a good deal of "neatness" about it. This gives some hope that clever methods can be found to uncover a correlated set of observables - that is, a set of projection operations whose outputs (observables) are found to exhibit some relationship to each other. This is not an easy assignment, and only a few have made much progress in finding such projections[11].

[1] Mécanique analytique (1788) "No figures will be found in this work, only algebraic [analytic] operations"; Théorie des fonctions analytiques (1797)

[2] E. T. Whittaker, A Treatise on the Analytical Dynamics of Particles and Rigid Bodies, with an introduction to the problem of three bodies (1904)

[3] M. Morse, preface to George David Birkhoff; Collected Mathematical Papers, Amer. Math. Soc. (1950)

[4] L. Brillouin, Scientific Uncertainty and Information (Academic Press, 1964)

[5] E. A. Jackson, Perspectives of Nonlinear Dynamics, Vols. 1 & 2 (Cambridge Univ. Press, 1991)

[6] E. N. Lorenz, “Deterministic nonperiodic flow” J. Atmos. Sci 20, 130-141 (1963) E. N. Lorenz, “The Essence of Chaos” (Univ. Washington Press, 1993)

This contains a reprint of his talk in December 1972, “Predictability: Does the flap of a butterfly’s wings in Brazil set off a tornado in Texas?”. In this he makes the more profound observations: (1) If a single flap of a butterfly’s wings can be instrumental in generating a tornado, so also can all the previous and subsequent flaps of its wings, as can the flaps of the wings of millions of other butterflies, not to mention the activities of innumerable more powerful creatures, including our own species. (2) If the flap of a butterfly’s wings can be instrumental in generating a tornado, it can equally well be instrumental in preventing a tornado.

[7] The idea that all dynamic phenomena should be able to be described by a digital computer, which works on rational numbers rather than the infinitesimals of calculus, has been a vision of Edward Fredkin for at least 20 years.

In fact Feynman had long ago expressed his concern with the infinite refinement of calculus:

> “It always bothered me that, according to the laws as we understand them today, it takes a computing machine an infinite number of logical operations to figure out what goes on in no matter how tiny a region of space, and no matter how tiny a region of time. How can all that be going on in that tiny space? Why should it take an infinite amount of logic to figure out what one tiny piece of space/time is going to do? So I have often made the hypothesis that ultimately physics will not require a mathematical statement, that in the end the machinery will be revealed, and the laws will turn out to be simple, like the checker board with all its apparent complexities. But this speculation is of the same nature as those other people make - ‘I like it’, ‘I don’t like it’, - and it is not good to be too prejudiced about these things.” - R. P. Feynman, The Character of Physical Law, p. 57

E. Fredkin has made a point of publishing very few papers. One of these is: Digital Mechanics, Physica D 45, 254-270 (1990). A concise rendition:

> “When rolled into one ball of wax, we are suggesting that DM (Digital Mechanics) may be able to model all of microscopic physics; and model it exactly.” E. Fredkin (10/88)

An indication of its possible importance can be inferred from:

> “The program that Fredkin is always pushing, about trying to find a computer simulation of physics, seems to me to be an excellent program to follow out. He and I have had wonderful, intense, and interminable arguments, and my argument is always that the real use of it would be Quantum Mechanics,... and by golly, it’s a wonderful problem, because it doesn’t look so easy.” R. P. Feynman, Simulating Physics with Computers, Int. J. Theor. Phys. 21, 467-488 (1982)

For some popularized, but sometimes rather muddy, accounts of Fredkin's views, see R. Wright, Did the Universe Just Happen?, The Atlantic Monthly, p. 29 (4/1988), and Three Scientists and their Gods, (Times Books, 1988)

Also, in an interview, reported in Computers in Physics, 8:3, 239 (1994), Stephen Wolfram remarked about a book that he has been working on:

> "My idea has been to see whether one can start from scratch. Ignore calculus, ignore all of these kinds of traditional mathematics, and just start from things that are easy to describe from a computational point of view, things that can be described by one line of Mathematica code, and say 'Can you use those kinds of basic algorithmic structures for making models in science?'. The basic answer, which I hope that my book will elaborate greatly on, is 'yes'."

He is apparently about to publish (1996) a book "A New Kind of Science" - "You look at a simple computer program, and it's very different from what you would expect.... If one looks at the history of science that arose at the time of Newton, it can be argued there has not been much of a new idea since then. I'm trying to make such a new idea - a new basis for thinking about science ... a whole host of new issues one can start to tackle."

[8] D. Lane, "Artificial Worlds and Economics, Parts I and II." J. Evolutionary Economics 3, 89-107, 177-197 (1993)

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T. Ray, "An Evolutionary Approach to Synthetic Biology: Zen and the Art of Creating Life", Artificial Life 1, 195-226 (1994)

T. Ray, "Evolution, Complexity, Entropy, and Artificial Life", Physica D 75, 239-263 (1994)

J. Casti, "Would-be Worlds: On the Creation of Societies in Silicon" (J. Wiley, 1996)

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T. Toffoli and N. Margolus, "Cellular Automata Machines: a new environment for modeling" (MIT Press, 1987)

[11] J. P. Crutchfield, "Discovering Coherent structures in Nonlinear Spatial Systems" Santa Fe Institute Working Paper, 91-09-034 (1991)

J. P. Crutchfield and M. Mitchell, "The Evolution of Emergent Computations" Santa Fe Institute Working Paper 94-03-012 (1993)

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5 Transforming Component (II):

Information to knowledge (understanding); understanding based on the discovery of relationships between observables, concurrent and sequential; understanding based on "associating" logically distinct forms of information from different sources; generalizations and refinements of "scientific methods"; new technical features and complications.

The process of turning scientific information into scientific knowledge, meaning an "understanding" of some phenomenon, is essential for any scientific progress - without this we are simply collecting data. As Poincaré expressed it, "Facts do not speak", or even more meaningfully:

"Science is built up with facts as a house is with stones. But a collection of facts is no more science than a heap of stones is a house."

This captures the insight that a heap of stones only becomes a house when one establishes some relationship between the stones. So it is with the observables within Science. It is such relationships that make collections of facts meaningful. The primal form of understanding within science is the discovery of some relationship between a set of observables. With the recognition of this basic fact, we see that Western Science in fact has a kinship with the wisdom of ancient Eastern cultures; their correlative view of the world (see references to Needham in section 2). As also noted in the association of MM to MO, the mathematics of topology has introduced a formal method to capture some of the correlative (holistic) features of dynamic systems. Here we consider understandings acquired from the empirical aspects of such relationships.

Such relationships can take one of two forms. The first form is a "concurrent" relationship - that is, expressing a time-independent relationship between observables. These are found in all of the historic "laws" of physics or elsewhere. Examples are Kepler's laws of planetary motion, the perfect gas law, PV = nRT, or Ohm's Law (voltage = resistance times the current, V = RI), or Hubble's relationship between the distance of a galaxy and its receding velocity, or the quantum mechanical uncertainty relations, etc.

The other relationship is "sequential" in character - how a set of observables at one time relate to their state at the "next" instant of time. With the introduction of calculus, the "next" instant of time was taken to be infinitesimally small (mathematically), whereas Poincaré introduced his "map" dynamics, involving widely separated instants of time. In fact, all physical observations necessarily deal only with discrete (finitely-separated) times, an issue we will return to shortly.

The concept of the "scientific method" inherited and modified since the times of R. Descartes and F. Bacon, has largely been superseded by other visions of how scientific observations and theories of some phenomenon should be brought into conjunction, "validating" our understanding [1-4]. I have no intention in getting involved in these highly philosophical entanglements. Rather, I simply want to point out some important technical facts, some of them new, and nearly all of them overlooked in philosophical discussions. As seen in the last section, these technical facts are often of a "refined" character, which may seem more of academic than scientific interest - but times are changing. The new knowledge we have about dynamic phenomena will clearly be of great importance in our understanding of complex phenomena. So let me outline a few of these new ideas and concerns.

In contrast with the simple "scientific method" structure outlined in section 2, we now have the three sources of information discussed in the last section. That means that the technical possibilities for "understanding" any natural phenomena has been greatly changed and expanded. There are now two logically- based sources of information, and these can be used in new inventive ways to help us certify our understanding of observations of some natural phenomenon, some of which have just been described. So we now have an information structure of the character

NP

PO

A **A**

CE $\rightarrow$ **CO** **A** **MO** $\leftarrow$ **MM**

That is, from natural phenomena (NP) we obtain physical observables (PO); from mathematical models (MM) we deduce mathematical "observables" (MO); from computer explorations (CE) we extract some comprehensible computational "observables" (CO). Our understanding of some phenomena is based on discovering or predicting some relationship between the observables in one or more of these sources. As noted in the discussion of ancient science, such relationships were discovered by Archimedes and Pythagoras, and the mathematics was limited to algebraic equations in their observables. It will be noted how simple and natural this process of "validation" was in those good old days. They didn't have to be concerned with mathematics involving all of the real numbers, just some integers and ratios (until the square root turned up!). But all that was changed with the invention of calculus, with its infinitesimals, limits, derivatives, continuity, concepts, etc. And, of course, computers put out an incomprehensible amount of data - which is to be distinguished from information, which implies a comprehensible observable... something that we can all agree on.

So a new difficulty has arisen, which has played essentially no role in science up to now. This new difficulty is the recognition that the observables PO, MO, and CO can all be logically distinct from each other. Specifically, if these observables are represented by numbers, then the set of numbers used in each case are logically distinct. By this

I mean that there is no logical connection between them - technically put, the possible "associations" between any two of the three observable sets (represented by A in the last figure) is many-to-one in either direction.

More specifically, the numbers in MO generally consist of all the real numbers, whereas those in CO are some bounded set of integers, and the numbers associated with PO are partitions of the real numbers (i.e., an integer, together with an integer range, due to instrumental output). Thus, relationships in one of the sets of observables (MO, CO, PO) can not be uniquely associated with relationships in any other set. This is not a serious problem if the phenomena one is trying to understand can be represent in some "coarse" fashion; then some rough "association" between these observable sets may be acceptable - which has historically been the case.

This, however, has already changed. Indeed it changed at the beginning of this century. This was appreciated by Duhem, and discussed in remarkably prophetic sections of his book [5], far ahead (1906) of the others noted above. It appears that few modern scientists yet appreciate this disjunction between some MO- understandings and the search for PO-understandings, possibly indicating the scientific meaninglessness of certain reasonably sounding physical questions. As Lorenz noted [6], Poincaré was not interested in these physical questions, but only in the mathematical aspects. Thus he never drew any of the profound physical implications to Science from his remarkable mathematical discoveries, as was done by Duhem. I believe that the recognition of these facts will lead to some dramatic transformations in our conception of scientific understanding - at least in those areas in which complex phenomena may be governed by "refined/sensitive" phenomena.

To make this more specific, let me present a few of Duhem's insightful remarks. In his book [5], he entitled section 3.3 "An example of mathematical deduction than can never be utilized", which is very interesting, but focused on an abstract mathematical example due to Hadamard. Of greater physical interest was his appreciation, in section 3.4, of the distinction between the mathematical interest in the stability of the gravitational three-body problem, and the quite distinct concern of astronomers in this same question. Duhem recognized, as Poincaré did not, that Poincaré's conjecture (which was made precise in the Birkhoff- Poincaré theorem [7]) meant that the problem of the stability of the solar system, is quite meaningful to mathematicians, "...for the initial positions and velocities of the bodies are for him elements known with mathematical precision. But for the astronomer these elements are determined only by physical procedures involving errors which will gradually be reduced by improvements in the instruments and methods of observation, but will never be eliminated. It might be the case, consequently, that the problem of the stability of the solar system should be for the astronomer a question devoid of all meaning; the practical data that he furnishes to the mathematician are equivalent for the latter to an infinity of theoretical data, neighboring on one another but yet distinct. Perhaps among these data there are some that would eternally maintain all heavenly bodies at a finite distance from one another, whereas others would throw some one of these bodies into the vastness of space...[so] any mathematical deduction relative to the stability of the solar system would be for the physicist a deduction that he could never use.” It is this insight, about the distinction between mathematical predictions and physical observations, which is little appreciated within the scientific community, to date.

The above discussion has to do with obtaining a form of “understanding” based on making some type of “association” between logically distinct types of information, PO, MO, and CO. As discussed at the beginning of this section, a more primal form of “understanding” requires the discovery of a relationship between a set of observables; a “correlative” understanding (see references to Needham in section 2). Here I will give only a few such examples in each of the informational groups.

(PO) –> **Physical Knowledge**:

Here I mean that some correlation between a set of physical observables has been discovered, yielding a primal form of understanding. Some important examples in recent years are:

The “impossible” periodic oscillations in some chemical systems - the Belousov- Zhabotinskii phenomena; dynamic correlations between a complicated set of chemical components.

The commonality in many physical systems (e.g., cardiac dynamics, chemical reactions, neural networks, ant colonies ?) of some correlated behavior of sets of observables, yielding spiral wave patterns [8].

Many experiments discovering correlations in the sequences of changes of dynamics (sequences of “bifurcations”), in Rayleigh-Taylor vortices, the Belousov- Zhabotinskii oscillations, many electrical and mechanical systems [9].

The bifurcation relationship; thermal “chaos” –> orderly vortical flows –> macro-chaotic flows [10].

The possible significance of the correlation between deterministic chaos and the functional response of the brain to sensory imputs [11].

The “fractal” qualities of many physical structures; “fractals” here are only an “association” with the mathematical fractal, of course! [12]

The search for methods of interactions with complex dynamic systems, such that the discovery of correlations will uncover basic dynamical information about such systems.[13]

Some of the general forms of knowledge that has (or may) come from this is:

* All structurally complex systems have chaotic modes of dynamics.
* The discovery of dynamic sensitivity means that systems are, to one degree or another, “responsive” to their environment. See how this factors into “bifurcation” diagram in section 7.

* In the biological systems, this understanding translates into various forms of sensitivity (the ability to respond) to environmental factors. This leads to the possibility of understanding adaptive and functional capabilities.

* Within the brain, sensitivity may be responsible for **extra-sensory** phenomena at the subconscious and conscious levels of cognition. This is certainly food for thought!

MO –> Mathematical Knowledge

** The correlations of the solutions obtained from the Poincaré-Birkhoff theorem, gave the essential new insight that "simple" MMs can have unimaginably complex families of dynamic solutions [7].

** Kolmogorov-Arnold-Moser established the fact that some dynamic order can be related to other dynamic "chaos" - that chaos need not be a uniform feature in the phase space.

** Levinson (around 1945) proved that the behavior of a periodically forced limit cycle has dynamic solutions that are as random in character as that obtained from tossing a coin. He introduced the idea of relating dynamics to symbolic sequences (such as the heads and tails of a tossed coin). Thus another qualitative characterization of dynamics joins topology and sets.

** Gardner-Greene-Kruskal-Miura discovered how to mathematically establish the relationship within some PDEs, which will yield long-time coherent, localized wave pulses ("solitons")

An introduction to all these topics can be found in my books [9].

Some general insights one gains from these results are:

I1 • One can expect orderly behavior and find instead chaotic relationships

I2 • One can expect the dispersal of a disturbance and find a sustained coherence

CO –> Computational Knowledge

The Fermi-Pasta-Ulam study (1954) of the dynamics of a lattice of atoms was initiated to see how fast this system would approach thermal equilibrium from a nonequilibrium state. An estimate of this rate could be obtained from Fermi's "golden rule" approximation. To their surprise they found that the system did not approach equilibrium, but rather the system returned periodically near to its initial nonequilibrium state, so correlations persisted. Fermi remarked that this was "a small discovery" [14]. Unfortunately he did not live long enough to further contribute to these new insights.

Insight: While thermal equilibration ("chaos") might be expected, orderly periodic behavior was found. (Related to I2, above).

This result inspired Zabusky and Kruskal to study the dynamics of pulses in the continuum approximation of such lattices. Instead of finding a fluid "hill" to disperse, they found localized traveling "solitons" , which persisted even after they collided with each other.

Insight: The expected breakup of colliding fluid "hills" was found not to occur; rather, the correlation that produces these "hills", is preserved. (Another case of I2)

These two unexpected "conservations" are related phenomena to I2 (above), and connected to the mathematical results of Kolmogorov, Arnold, and Moser.

There have been seemingly endless studies of the dynamics of the "Logistic map", $x(t+1) = c * x(t) * (1 - x(t))$, which was inspired by ecological considerations [15]. These have led to Feigenbaum's quantitative, period-two "universal" bifurcation sequence, intermittency, crises, and relationships between different types of dynamics, captured in the "universality" of bifurcation sequences (Metropolis, Stein, and Stein symbolic patterns) [16], to mention only a few.

Discovery of fractal relationships between basins of attraction: "Basins of Wada" [17] and "Riddled" basins of attraction [18].

Long-time integration of the dynamics of the solar system [19]. A recent example involves around 200 million years) led to the discovery of chaos within our solar system (the tilt of the spin axis of Mars, with an obliquity variation of 0 to 60 degrees on the scale of several million years [20].

One of the most important computational discovers of chaotic dynamics was the one made by Edward Lorenz [21]. In a fine example of a true computational exploration, using a cleverly selected "toy" meteorological model, he discovered that the attractor dynamics that he obtained was very sensitive to the initial conditions he used. This led to the common characterization of the "butterfly effect", and the general concept of a "strange attractor", which was discussed briefly in section 4 (see figure 7).

It is well worth reviewing what Lorenz actually said about this "butterfly effect", because it is much more profound than is generally appreciated. The talk, on December 29, 1972, from which this expression originated was entitled "Predictability: Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?" [22]. It should be read in its entirety, even though he leaves the question unanswered. For the present purpose, we will only consider Lorenz's leading two propositions:

1. "If a single flap of a butterfly's wings can be instrumental in generating a tornado, so also can all the previous and subsequent flaps of its wings, as can the flaps of the wings of millions of other butterflies, not to mention the activities of innumerable more powerful creatures, including our own species.

2. If the flap of a butterfly's wings can be instrumental in generating a tornado, it can equally well be instrumental in preventing a tornado."

The first makes the point that the effect of a small disturbance, acting on a sensitive system, can have a significant macroscopic effect in the future. This "causal" aspect ("sensitivity to initial conditions") is what is usually the focus of attention by scientists. But it also contains another message which is really more important, because it draws attention to the importance of "subsequent flaps...", that is, to the continual response of a sensitive system to its environment (nothing "initial" here).

Moreover, the second point made is that another disturbance acting on this sensitivity can eliminate the first effect - provided, of course, that the two disturbances are appropriately correlated in space-time (the second disturbance can not eliminate an existing tornado, but it may join with the first at some point to negate its influence). Thus, both the time scales, and even the possibilities of certain effects, can vary widely. "chaos/sensitivity" is characterized by its very inhomogeneous properties, depending on time scales, the type of phenomenon, and details in the location and type of perturbations. There is no known general characterization of this micro-to- macro influence. However, there remains this very valuable Lorenz-insight:

L-Insight: Sensitive systems are continually influenced, to one degree or another, by the correlated actions of a multitude of unknown small disturbances

These are but a few of many possible examples, but hopefully give some impression of the diversity of these new sources of information.

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6 The “Inward-Bound” $\leftrightarrow$ “Outward-Bound” Bifurcation within Physics:

Conflicting concepts of reductionism within Science; the metaphysics of faith vs. constructionism.

During the latter half of this century we have seen a division develop within the physics community, which represents a fundamental bifurcation in physicists’ viewpoints as to what science and “reductionism” is about, or what it should be about in the future[1]. In this section we will have a look at some of the conflicting opinions of eminent scientists of this century, not just for the sociological impact they have on science, and the public perception of science, but because, in reviewing these differences we may sense some of their technical weaknesses and strengths; and perhaps be inspired to find new visions for unifying all of Science in the future - if we’re lucky.

One group of physicists, interested in high-energy phenomena, has a number of vocal and influential members, who, perhaps led by the early visions of Einstein (1918), aspire to determine a set of irreducible laws, which are capable of giving “a complete description of the universe we live in” [1] at least in principle (the beloved “in principle” principle). The second group consists of physicists interested in physical phenomena in ionized and neutral gases, simple and complex fluids, solids, biological systems, and low-temperature materials.

The focus of these two groups has led to a metaphysical bifurcation within the physics community, which is significantly related to the energetic bifurcation in their research interests; what might be characterized as the “inward-bound” [2] $\leftrightarrow$ “outward-bound” bifurcation:

High-Energy	**Lower-Energy**
⟵ Inward-Bound (IB)	**Outward-Bound (OB)⟶**
Highly Stable Structures	**Meta-Stable Structures**
Environmentally Insensitive	**Environmentally Sensitive**
“irreducible laws?”	**“infinite horizons”**

To appreciate the character and the depth of the division which has developed between some members of these two groups, it is necessary to read at least some of their views about science. What follows will be very limited, and is not intended to be a scholarly summary of this issue; the references will lead you to more complete discussions. The purpose of this exercise is to distinguish issues of faith and those viewpoints which may lead to a constructive foundation of Science, which hopefully will point to some united scientific program in the future. This will be explored further in the next section.

[1] A recent, candid account of the reductionistic bifurcation that occurred between molecular biologists and classical biologists, following J. D. Watson’s appointment to the Harvard faculty in 1956, has been given by Edward O. Wilson, in his delightful memoir ”Naturalist”, Chapter 12: “The Molecular Wars”.

Before presenting the views of some of the inward-bound (IB) physicists, let me refer to a few quotations, which are precursors to some IB scientists' view of science.

These ideas are based, in part, on the presumed power of rational thought and mathematics. Following Pythagoras' early association of mathematics and nature, the first metamorphosis of science also involved the impact of mathematics on the philosophy of some scientists, as illustrated by René Descartes belief that "Only when the results in every science were as clear, controllable, and certain as those in mathematics would the claim to have attained knowledge be justified." During the present century, Einstein has offered rather mixed messages on this subject. On the one hand, he told the Prussian Academy of Science in 1921: "As far as the propositions of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality."[3] However, this remark was sandwiched between two other statements, on different occasions. In 1918, Einstein expressed the view [4]:

> "In regard to his subject matter ... the physicist has to limit himself very severely; he must content himself with describing the most simple events which can be brought within the domain of our experience.... Does the product of such a modest effort deserve to be called by the proud name of a theory of the universe?
>
> In my belief the name is justified.... With them [the general laws of theoretical physics] it ought to be possible to arrive at the description...of every natural process, including life, by means of pure deduction, if that process of deduction were not far beyond the capacity of the human intellect. The physicist's renunciation of completeness for his cosmos is therefore not a matter of fundamental principle.
>
> The supreme task of the physicist is to arrive at those universal elementary laws from which the cosmos can be built by pure deduction."

Restated, Einstein believed that the universe is governed by universal elementary laws, which it is the task of the physicist to obtain, since *in principle*, if it were not far beyond the capacity of the human intellect, they could be used to build the cosmos by pure deduction.

Later [5], Einstein gave a more expansive presentation of this view, which contained some important qualifications that have been repeatedly applied by others in more modern times, so let me quote at more length:

> "Even at the expense of completeness, we have to secure purity, clarity and accurate correspondence between the representation and the thing represented. When one realizes how small a part of nature can thus be comprehended and expressed in an exact formulation, while all that is subtle and complex has to be excluded, it is only natural to ask what sort of attraction this work can have? Does the result of such self-denying selection deserve the high-sounding name of World-Picture?

> I think it does; because the most general laws on which the thought-structure of theoretical physics is built have to be taken into consideration in studying even the simplest events in nature. If they were fully known one ought to be able to deduce from them by means of purely abstract reasoning the theory of every process of nature, including that of life itself. I mean theoretically, because in practice such a process of deduction is entirely beyond the capacity of human reasoning. Therefore the fact that in science we have to be content with an incomplete picture of the physical universe is not due to the nature of the universe itself but rather to us.
>
> Thus the supreme task of the physicist is the discovery of the most generally elementary laws from which the world-picture can be deduced logically."

A very significant part of this "world-picture" vision is captured in his clarification: "I mean theoretically, because in practice such a process of deduction is entirely beyond the capacity of human reasoning." It is from this stance, that attributes general theoretical power to "the most general laws", in contrast to the real effective problem of deductive reasoning, which today is avoided by employing the "in principle" principle, as is often seen in what follows.

The form of reductionism that arose from this, at least the one espoused (in varying degrees) by Weinberg and many of the high-energy community, retains this "theoretical", or "in principle" conception. Indeed, in its most defensible and pure form, the reductionism of Weinberg divorces itself from the whole question of how we are to understand most natural phenomena. This form of reductionism is totally fixed on the view that the "laws of nature" are only those "fundamental" laws that are uncovered at the highest end of the energy spectrum; involving the extreme reductions of matter - the most elemental laws, in the sense that they will ultimately ¡perhaps¿ not be reducible into more basic laws. They are certainly not the most "fundamental laws of nature" in the sense of understanding our world. The very concept of such "laws" will require re-evaluation.

Before turning to the views of more recent scientists, let me quote from a talk given in 1896 by the German physicist, Emil Wiechert, to the Physics and Economics Society of Königsberg of East Prussia - whose a vision of science was totally at variance with Einstein's subsequent program for physics:

> "The matter which we suppose to be the main constituent of the universe is built out of small self-contained building-blocks, the chemical atoms. It cannot be repeated too often that the word "atom" is nowadays detached from any of the old philosophical speculations: we know precisely that the atoms with which we are dealing are in no sense the simplest conceivable components of the universe. On the contrary, a number of phenomena, especially in the area of spectroscopy, lead to the conclusion that atoms are very complicated structures. So far as modern science is concerned, we have to abandon completely the ideas that by going into the realm of the small we shall reach the ultimate foundations of the universe. I believe we can abandon this idea without any regret. The universe is infinite in all directions, not only above us in the large

but also below us in the small. If we start from our human scale of existence and explore the content of the universe further and further, we finally arrive, both in the large and in the small, at misty distances where first our senses and then even our concepts fail us."

However, this beautiful, inexhaustible, and prophetic view of science, was dominated for over half a century within physics by Einstein's vision, and its modern extensions, to be presented shortly. Dyson [7] uses the Einstein-Wiechert contrast as an example of the division he sees between the science that dominates the academic community and the one that is dominate in the industrial community. He refers to the former as "unifiers" and the latter as "diversifiers", and draws parallels with such pairs as Athens and Manchester, and Descartes and Bacon. The terminology "unifiers", does not imply any program that will unify our understanding of the various branches of science, but rather the belief that we can capture, largely by our powers of reasoning, a deductive understanding of all natural phenomena.

What follows will be a very limited collection of quotations relevant to reductionism. The scientists' views will be presented in roughly chronological order (several at different times), which illustrates the state of this metaphysical bifurcation in the latter half of this century. The selection of thoughts will be from:

Richard Feynman, David Bohm, Philip Anderson, Victor Weisskopf, Ernst Mayr, Steven Weinberg, Stephen Hawking, Anthony Leggett, Leo Kadanoff, Murray Gell-Mann

As already mentioned, the purpose of the present exercise is not only to illustrate this metaphysical bifurcation, but to search for visions that can help to forge a new "meta-science", to be taken up in the next section. We begin with a stimulating high-point:

Richard Feynman

These quotations are drawn from his wonderful set of Messenger Lectures on the character of physical laws, given at Cornell University in 1964 [8]. One should really read these selections within their entire context, to appreciate his full message; but let me illustrate some points, beginning with [p. 122]:

> "In fact, although we have been talking in these lectures about the fundaments of the physical laws, I must say immediately that one does not, by knowing all the fundamental laws as we know them today, immediately obtain an understanding of anything much. It takes a while, and even then it is only partial. Nature, as a matter of fact, seems to be so designed that the most important things in the real world appear to be a kind of complicated accidental result of a lot of laws."

He then gave a description of “a kind of complicated accidental result”, and “a lot of laws”, which emphasizes our inability to deduce many results - what some might refer to as “emergent” phenomena - even when the basic laws are assumed to be known. His example is particularly beautiful [pp. 122-125]:

> “To give an example, nuclei, which involve several nuclear particles, protons and neutrons, are very complicated.... But the remarkable thing about nature is that the whole universe in its character depends upon the position of one particular level in one particular nucleus. In the carbon 12 nucleus, it so happens, there is a level at 7.82 million volts. and that makes off the difference in the world.”

He then went on to explain how Hoyle and Salpeter pointed out that three helium nuclei could fuse to form carbon only if there happened to be an energy level at 7.82 million volts - for this would allow the helium atoms to stay together sufficiently long, on the average, for the fusion to take place. Thus this energy level was needed to explain how carbon was formed in stars, from which the production of the heavier elements could be understood. He ended with:

> “And so, by a back-handed, upside-down argument, it was predicted that there is in carbon a level at 7.82 million volts; and experiments in the laboratory showed that indeed there is. Therefore the existence in the world of all these other elements is very closely related to the fact that there is this particular level in carbon. But the position of this particular level in carbon seems to us, knowing the physical laws, to be a very complicated accident of 12 complicated particles interacting. This example is an excellent illustration of the fact that an understanding of the physical laws does not necessarily give you an understanding of things of significance in the world in any direct way. The details of real experience are often very far from the fundamental laws.”

In this developing metamorphosis of science, one of the basic issues that needs to be clarified is what characterizes how “far” we are from any known “laws”. This naturally leads to issues involving “levels” of knowledge, within various “hierarchies”. In this vein, Feynman continued [pp. 124-126]:

> “We have a way of discussing the world, when we talk of it at various hierarchies, or levels. Now I do not mean to be very precise, dividing the world into definite levels, but I will indicate, by describing a set of ideas, what I mean by hierarchies of ideas.
>
> For example, at one end we have the fundamental laws of physics. Then we invent other terms for concepts which are approximate, which have, we believe, their ultimate explanation in terms of the fundamental laws. For instance, ‘heat’. Heat is supposed to be jiggling, and the word for a hot thing is just the word for a mass of atoms which are jiggling. But for a while, if we are talking about heat, we sometimes forget about the atoms jiggling - just as when we talk about the glacier we do not always think of the hexagonal ice

and the snowflakes which originally fell. Another example of the same thing is a salt crystal. Looked at fundamentally it is a lot of protons, neutrons, and electrons; but we have this concept 'salt crystal' which carries a whole pattern already of fundamental interactions. An idea like pressure is the same.

Now if we go higher up from this, in another level we have properties of substances - like 'refractive index', how light is bent when it goes through something; or 'surface tension', the fact that water tends to pull itself together, both of which are described by numbers. I remind you that we have to go through several laws down to find out that it is the pull of the atoms, and so on. But we still say 'surface tension', and do not always worry, when discussing surface tension, about the inner workings.

On, up in the hierarchy. With the water we have waves, and we have a thing like a storm, the word 'storm' which represents an enormous mass of phenomena, or a 'sun spot', or 'star', which is an accumulation of things. And it is not worth while always to think of it way back. In fact we cannot, because the higher up we go the more steps we have in between, each one of which is a little weak. We have not thought them all through yet.

As we go up in this hierarchy of complexity, we get to things like muscle twitch, or nerve impulse, which is an enormously complicated thing in the physical world, involving an organization of matter in a very elaborate complexity. Then come to things like 'frog'.

And then we go on, and we come to words and concepts like 'man', and 'history', or 'political expediency', and so forth, a series of concepts which we use to understand things at an ever higher level.

And going on, we come to things like evil, and beauty, and hope... .

Which end is nearer to God; if I may use a religious metaphor. Beauty and hope, or the fundamental laws? I think that the right way, of course, is to say that what we have to look at is the whole structural interconnection of the thing; and that all the sciences, and not just the sciences but all the efforts of intellectual kinds, are an endeavor to see the connections of the hierarchies, to connect beauty to history, to connect history to man's psychology, man's psychology to the working of the brain, the brain to the neural impulse, the neural impulse to the chemistry, and so forth, up and down, both ways. And today we cannot, and it is no use making believe that we can, draw carefully a line all the way from one end of this thing to the other, because we have only just begun to see that there is this relative hierarchy.

> And I do not think either end is nearer to God. To stand at either end, and to walk off that end of the pier only, hoping that out in that direction is the complete understanding, is a mistake. And to stand with evil and beauty and hope, or to stand with the fundamental laws, hoping that way to get a deep understanding of the whole world, with that aspect alone, is a mistake. It is not sensible for the ones who specialize at one end, and the ones who specialize at the other end, to have such disregard for each other. (They don't actually, but people say they do.) The great mass of workers in between, connecting one step to another, are improving all the time our understanding of the world, both from working at the ends and working in the middle, and in that way we are gradually understanding this tremendous world of interconnecting hierarchies."

This is certainly one of the more beautiful conceptualizations of scientific hierarchies (in the plural) that I have encountered. It retains the flexibility, wonder, and humility, appropriate in our attempts to understand this beautifully complex world. It stands in sharp contrast with both Einstein's and some very recent visions of scientists' goals. In particular, Feynman's references to the lack of one "Godly end", differs markedly with both Einstein and Hawking, retaining some of Wiechert's infinite-in-all-directions wonderment. On the other hand, this conceptualization of hierarchies does not contain enough structure to allow one to generate a much needed "constructional program" for the future of Science - to which we return later.

<u>David Bohm</u>

David Bohm was a physicist with a long-abiding interest in foundational issues of science - and certainly one of the most original, exploratory thinkers in this quest for understanding. In this section, I will present some of his early (1957) views on fundamental matters that relate to reductionistic issues [9]. He appears to have rarely discussed reductionism directly as such. However, his conception of the indivisibility of the universe, and the inexhaustible diversity of the "things" we observe, naturally bear upon such concerns. His views about the duality of probabilistic and deterministic laws, the "context" of our understandings, the "contradictory" character of some motions, that everything we view as independent objects (processes, etc.) are but temporary manifestations out of this wholeness; the ephemeral character of our lives being a simple case in point. These unique and stimulating perspectives stand in sharp contrast to what most physicists learn and are concerned with. I believe that Bohm's ideas are worthy of serious attention, and need to be responded to at some level in the future. I will indicate in the next section that points of contact can be made between his concerns and those of a "constructional metascience."

Bohm explored the connections (in both directions) between deterministic and probabilistic laws of nature. For example, after a discussion of ideas by von Mises (1951), Bohm notes [p. 64]:

> "This means, however, that, whereas he (von Mises) admits that determinate laws can arise as approximation to the effects of laws of probability, which hold

> where large enough numbers of objects or events are involved, he supposes that no analogous possibility exists by which laws of probability can arise as approximations to the effects of determinate laws. Thus, in this point of view, laws of probability are regarded as having a more fundamental character than is possessed by determinate laws." (as is the usual interpretation of quantum mechanics). Bohm referred to this as "indeterministic mechanism".

He then [p. 65] raised the question as to "whether the details of chance fluctuations are ever really completely arbitrary and lawless relative to all possible contexts":

> "For example, it has been proved mathematically [10] that there exists a wide class of determinate sequences involving complicated chains of events or events determined by a large number of independent causal factors, which possess, to an arbitrarily high degree of approximation, the essential statistical properties that are characteristic of distribution treated in terms of the theory of probability."
>
> "Thus, one sees that the possibility of treating causal laws as statistical approximations to laws of chance is balanced by a corresponding possibility of treating laws of probability as statistical approximations to the effects of causal laws".

Hence Bohm contends that this is so, if we "broaden the context" of the causal laws. A more specific description of one "context", in which there is a deterministic-probabilistic type of duality, will be outlined in the next section.

Bohm introduced the term "levels" without much specificity, as can be seen in his remarks [p. 66]:

> "...there is no conceivable way of proving that the laws of the various levels and of qualitative changes are completely and perfectly reducible to those of any given quantitative theory, however fundamental that theory may seem to be."
>
> "Each level enters into the substructure of the higher levels, while, vice versa, its characteristics depend on general conditions in a background determined in part in other levels both higher and lower, and in part in the same level"

This lack of specification is certainly related to Bohm's vision of the diversity and transitory autonomy of parts of nature. Thus [p. 139]:

> "There is, however, one general statement that can be made at this point about the inexhaustible diversity of things that may exist in the universe; namely, that they must have some degree of autonomy and stability in their modes of being. Now, thus far, we have always found that such autonomy exits. Indeed, if it did not exist, then we would not be able to apply the concept of a "thing" and there would then be now way even to formulate any laws of nature. For how can there be an object, entity, process, quality, property, system, level, or whatever other thing one cares to mention, unless such a thing has some

> degree of stability and autonomy in its mode of existence, which enables it to preserve its own identity for some time, and which enables it to be defined at least well enough to permit it to be distinguished from other things?"

and [p. 141]

> "Hence, the determinations of any purely causal theory are always subject to random disturbances, arising from the chance fluctuations in entities, existing outside the context treated by the theory in question."

This reference to relative autonomy in modes of being, which is maintained over some range of variation of the conditions in which they exist ("context"?), arises naturally in the "projections", NP $\to$ PO, discussed in section 4, and in the metastable concepts of the bifurcation figure at the beginning of this section. These ideas will be expanded upon in the next section.

Bohm was also very sensitive to the issues of the "process of becoming"; the fact that change is an integral aspect of all things in nature [p. 147]: "In sum, then, no feature of anything has as yet been found which does not undergo necessary and characteristic motions", where, by "motions" he meant any transformation of a "thing" (e.g., within astronomy, biology, geology, etc.). It is interesting to note that Turing, in his seminal dynamic treatment of a morphogenetic processes [11], also pointed out that "Most of an organism most of the time, is developing from one pattern into another, rather than from homogeneity into a pattern." In more recent times, the study of "continually adaptive" processes is directly involved in such issues.

In this focus on motions, Bohm noted that these motions contain within them a great many relatively independent and "contradictory" tendencies. For example, in astronomy, some systems of stars are disrupted, others are formed, due to chance disturbances from other galaxies; on the earth storms earthquakes, etc., which are of chance origin relative to the life of an individual, may produce conditions in which the individual cannot continue to exist. Contradictory tendencies must exits in order for many things to possess characteristic properties which help define what they are; a gas would not have its characteristic properties if all the molecules of the gas moved together in a co- ordinated way.

> "We conclude, then, that opposing and contradictory motions are the rule throughout the universe, and this is an essential aspect of the very mode of things."

Continuing [p. 164]:

> "... we are led to understand nature in terms of an inexhaustible diversity and multiplicity of things, all of them reciprocally related and all of them necessarily taking part in the process of becoming, in which exist an unlimited number of relatively autonomous and contradictory kinds of motions. As a result no particular kind of thing can be more than an abstraction from this process, and abstraction that is valid within a certain degree of approximation, in definite ranges of conditions, within a limited context, and over a characteristic period of time."

While there are rather mystical elements in Bohm's visions, much can be connected with objective reality (communal observations), and correlated behavior even within the context of some "contradictory" motions. Indeed, much of what Bohm describes fits in quite naturally with concepts of the interactions of relatively autonomous, metastable "ensemble variables" at one level, being deductively related to some physical phenomenon at a higher level - the "ensemble" is dictated by nondeductive constraining conditions (e.g., environmental, historical, etc.) - Bohm's "contexts"?. In any case, a useful hierarchical form of understanding can be developed with such "ensemble variables" concepts, as will be discussed in the next section.

For some final views of Bohm, until the next section, [pp. 169-170]:

> "Now, the most essential and fundamental characteristic of the totality of matter in the process of becoming lies precisely in the fact that it can be represented only with the aid of an inexhaustible series of abstractions from it, each abstraction having only an approximate validity, in limited contexts and conditions, and over periods of time that are neither too short nor too long."
>
> "In our point of view, we admit that all the above things do actually colour and influence our knowledge; but we admit also that nevertheless there still exists an absolute, unique, and objective reality. To Know this reality better, and thus to correct and eliminate some of the preconceptions and lacunae that are inevitably in our knowledge at any particular time, we must continue our scientific researches, with the objective of finding more and more of the things into which matter in the process of becoming can be analyzed approximately, of studying in a better and better approximation the relationships between these things and of discovering in greater and greater detail what are the limitations on the applicability of each specific set of concepts and laws. The essential character of scientific research is, then, that it moves towards the absolute by studying the relative, in its inexhaustible multiplicity and diversity.
>
> "In other words,... the only absolute truth [is] that there is no absolute content to our knowledge at all."

To end this brief excursion into Bohm's unique visions, let me simply extract a few points for later use: (1) issues of stability and autonomy of all "things" for limited times; (2) that there can be complimentary probabilistic and deterministic aspects of nature; (3) that (somehow) we need to pay attention to the issue of the "contexts" of "things"; (4) that "motion" (changes) are an essential component of all features of nature (5) the only absolute truth is that there is no absolute content to our knowledge.

Philip Anderson

One of the early spokesmen for a realistic assessment of the scientific knowledge contained in our modern theories of science was Anderson [12]. Specifically, he wrote to oppose an early point of view that had been expressed by Weisskopf [13] (which was modified later, as will be seen), and illustrated in the passage:

> "Looking at the development of science in the Twentieth Century one can distinguish two trends, which I will call "intensive" and "extensive" research, lacking a better terminology. In short: intensive research goes for the fundamental laws, extensive research goes for the explanation of phenomena in terms of known fundamental laws. As always, distinctions of this kind are not unambiguous, but they are clear in most cases. Solid state physics, plasma physics, and perhaps biology are extensive. High energy physics and a good part of nuclear physics are intensive. There is always much less intensive research going on than extensive. Once new fundamental laws are discovered, a large and ever increasing activity begins in order to apply the discoveries to hitherto unexplained phenomena. Thus, there are two dimensions to basic research. The frontier of science extends all along a long line from the newest and most modern intensive research, over the extensive research recently spawned by the intensive research of yesterday, to the broad and well developed web of extensive research activities based on intensive research of past decades".

This totally misconstrues the impact of this "intensive" research (i.e., high- energy and nuclear physics) on our knowledge of most phenomena in nature. He would have us believe that intensive discoveries caused "a large and ever increasing activity" to explain "hitherto unexplained phenomena", and that "extensive research" is "spawned by the intensive research of yesterday", or "based on intensive research of past decades". Nothing could be much further from the historical facts. This will be clarified later.

Anderson was one of the first modern "established" physicists (being a Nobel Laureate helps) to openly oppose such a viewpoint. He began with the observations:

> "The reductionist hypothesis may still be a topic for controversy among philosophers, but among the great majority of active scientists I think it is accepted without question. The working of our minds and bodies, and of all the animate and inanimate matter of which we have any detailed knowledge, are assumed to be controlled by the same set of fundamental laws, which except under certain extreme conditions we feel we know pretty well.
>
> It seems inevitable to go on uncritically to what appears at first sight to be an obvious corollary of reductionism: that if everything obeys the same fundamental laws, then the only scientists who are studying anything really fundamental are those who are working on those laws. In practice, that amounts to some astrophysicists, some elementary particle physicists, some logicians, and a few mathematicians, and a few others. This point of view, which it is the main purpose of this article to oppose, is expressed in a rather well-known passage by Weisskopf", which is given above.

Anderson then remarked:

> "The effectiveness of this message may be indicated by the fact that I heard it quoted recently by a leader in the field of materials science, who urged the participants at a meeting dedicated to "fundamental problems in condensed matter physics" to accept that there were few or no such problems and that nothing was left but extensive science, which he seemed to equate with device engineering.
>
> The main fallacy in this kind of thinking is that the reductionist hypothesis does not by any means imply a "constructionist" one: The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. In fact, the more the elementary particle physicists tell us about the nature of fundamental laws, the less relevance they seem to have to the very real problems of the rest of science, much less to those of society."

It is unfortunate that we have allowed the elementary particle physicists to usurp the term "fundamental laws" for what they are investigating. It is much more accurate to describe these laws as the "elemental laws", because they refer only to the most elementary activities in nature. Hence, while some may take comfort in the assumption that all physical processes are controlled by these elementary laws, they have shed no light on our understanding of most natural phenomena. Moreover, there is no empirical bases for the assumption that the forces in the aggregate are simply linear combinations of these forces, found in our Hamiltonians. We know that this fails for gravity, according to Einstein's general theory of relativity. In addition, we have no empirical knowledge about the possibilities of weaker forces than presently known. We do know that both of these issues would have profound effects on the sensitive dynamics in the OB systems.

Anderson's view of these matters were:

> "The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it seems to me that one may array the sciences roughly linearly in a hierarchy, according to the idea: The elementary entities of science X obey the laws of science Y.

X	Y
solid state or many-body physics	elementary particle physics
chemistry	many-body physics
molecular biology	chemistry
cell biology	molecular biology
*	*
*	*
psychology	physiology
social sciences	psychology

> But this hierarchy does not imply that science X is "just applied Y". At each stage entirely new laws, concepts, and generalizations are necessary, requiring inspiration and creativity to just as great a degree as in the previous one. Psychology is not applied biology, nor is biology applied chemistry."

Anderson's conception of a hierarchy is more structured than Feynman's, and certainly Bohm's, but it does not yet suggest what the character of the "[not] just applied Y" actions, and the "new laws, concepts, and generalizations" might involve, and require, in order to accomplish this "constructionism" of which he spoke. He, of course, was well aware of methods used in solid state physics and elsewhere, to construct specific theories, but a generalization of concepts is still required.

Victor Weisskopf

In 1977, a decade after his above views were published [13], Victor Weisskopf wrote an extensive article [14], giving some revised views on the frontiers and limits of science. He retained the concept of two kinds of scientific frontiers, the external and the internal, now described as:

> "The external frontier delimits the exploration of those realms of nature that lie beyond currently understood principles. Typical external frontiers are represented by the fields of subnuclear research and astronomy. The subnuclear studies penetrate one step beyond nuclear physics.... The external frontier therefore is the place where we find new ways of natural behavior beyond the terrestrial limits of space and energy. Probably nature is subject to new laws or to still unknown extensions of our present laws when those limits are trespassed. In these areas the romance of discovery is especially manifest: we find unexpected and mysterious objects and processes that appear to be unexplainable and beyond any known laws of nature as we penetrate into the deeper and darker realms of the universe."

There is no doubt, from this recounting of the "romance of discovery ...into the deeper and darker realms of the universe", where Weisskopf spent much of his research life! However, he now discusses in some detail various "complexities", despite "understood principles".

> "The internal frontier is a much broader area where the basic principles are believed to be known but where the apparent complexity of the phenomena prevents us from understanding and explaining them. The internal frontier mostly concerns the first rung on the quantum ladder - the world of atoms and molecules.... However, while the principles on which the atom operates are understood, the complexities of that operation remain very great.
>
> Let me illustrate this in the following way. Assume that a group of intelligent theoretical physicists have lived in a closed building from birth and have never had any occasion to see structures in nature. All that these physicists are supposed to know are the fundamental principles upon which atomic structures is based - i.e., the existence of atomic nuclei and electrons, quantum mechanics, and the nature of electric forces. What would be the result if these physicists were asked to predict how the atom manifests itself in nature and to what structures it gives rise?
>
> They would most likely be able to predict that atoms exist; they could probably predict that atoms join to form molecules; and they might be able to describe what kinds of simple molecules actually exist in nature. They might even be able to forecast the formation of macromolecules or chains of molecules, the fact that molecules can join to produce solids, and the existence of many different solids such as metals, crystals, and salts. But I am most certain that these theorists would never predict the existence of liquids. A liquid is a highly complex phenomenon in which the molecules stay together yet move along each other; it is by no means obvious why such a strange substance should exist. In the same manner, a great deal of chemistry, and certainly the existence of life, would be impossible to predict. This is to illustrate that an understanding of the principles by no means implies and understanding of the world of phenomena."

He proceeded to make the following important observation:

> "When we face the realities of our environment, we deal with these structures and superstructures rather than with the atoms that make them up. This is why objects, concepts and ideas that the scientists uses when he tries to understand what goes on do not deal directly with atoms but rather with the structures that are immediately involved in the phenomena under study. This is the characteristic situation along the internal frontier of science."

He then gave a few examples of these "structures and superstructures", such as temperature, pressure, entropy, and phases, from thermodynamics, and chemical bonds and kinetics of reactions from chemistry.

> "Each of these concepts and principles are either known to be consequences of fundamental laws of atomic structure, or it is made plausible that they do not contradict them or require a change of, or addition to, the fundamental laws."

> "This raises and interesting question: Since we do not understand many, perhaps most, of the phenomena of complex and organized matter, how can we be sure that all the basic principles of the atomic world are known? How can we be so bold as to assume that we fully understand the fundamental laws that govern the behavior of atoms if so many structures, processes, and phenomena in our environment are not completely understood...? In spite of this, very few scientists today would maintain that there are new fundamental principles to be discovered with regard to life or the other phenomena I have mentioned."

Again, the attribution of "fundamental" is made to "laws" that have no relevance to our understanding of "perhaps most of the phenomena of complex and organized matter", and even the characterization that there are no "new fundamental principles to be discovered with regard to life or the other phenomena" he mentioned. "Fundamental" has a strange meaning indeed!

It is from this distortion of the fundamental character of efforts to understand complex phenomena, and the corresponding irrelevance of the "laws" at the atomic level to our understanding of most of these macroscopic phenomena, that produces the following misfocused observation:

> "...there is today a general belief that the basic principles of the atomic world are known and no additional law or principle is necessary in order to explain the phenomena of the atomic realm, including the existence and development of life. This assurance stems in large part from the fact that, while we cannot explain many complex phenomena, the complexity in itself is not surprising but plausible and expected."

On the contrary, whatever ones belief is concerning the completeness of "the basic principles of the atomic world", these "basic principles" play no role in our understanding of macroscopic, complex phenomena. That is the reason we need to search for such concepts as Weisskopf's "structures and superstructures". And to say that "the complexity in itself is not surprising but plausible and expected" hardly fits his own parable concerning the isolated physicists who would never have predicted the existence of a liquid, nor "a great deal of chemistry, and certainly the existence of life". It is also clear that he was unaware of the startling dynamic discoveries that had occurred over the three decades previous to his article, in such fields as electrical engineering, meteorology, biology, and astronomy.

Weisskopf gave a nice extended discussion of his rather unique concept of hierarchies in nature, starting with the nucleons, and electrons, then forming nuclei and atoms, then atoms forming molecules. But at this point he suggested that we consider two paths: one involving only inanimate objects while the other leads to living systems. Hence the first proceeds up the line of molecules to liquids and crystals, which form minerals and rocks, forming planets and stars, forming galaxies, and ultimately the universe. The second path leads from molecules to macromolecules, forming cells, forming multicellular species, some with brains. Individuals of a species may form groups, tribes, and societies.

"There is an obvious tendency of nature [to go] from disorder to order and organization.... Matter is never quite isolated from its surroundings and always loses its heat, which escapes in some highly unordered form of relatively large entropy. Hence the second law [of thermodynamics] requires an increase of order in a warm material when it is in contact with its surroundings.... I have called this conclusion the fourth law of thermodynamics."

"There is a distinction between order in living and dead nature. At the very end of everything, when the sun is extinguished, matter will be even more ordered than it is now, because all random heat motion will be frozen. But everything will be cold, dead, and unchanging. It is the temperature gradient between the hot sun and the colder Earth that produces the living order, ever changing and developing, through reproduction and evolution."

The important issue of "understanding" is touched upon only briefly:

"In this sequence of hierarchies the line between the external and internal frontiers must be drawn roughly at the atomic nucleus." All that is more macroscopic can "be thought, in principle, to be based upon atomic and molecular structure.... However, a knowledge of the basic laws is insufficient for a real understanding how the "parts" are related to the "whole" at each step of the hierarchies. ... Real understanding implies the distinction between the essential and the peripheral."

Thus the atoms are generally peripheral, whereas identifying the "structures and superstructures" is the essential task in finding the "parts" needed to "understand" the "whole". His defining remark on this issue was:

"The term understand should mean a general recognition that the phenomenon fits into the framework of science, that it is "demystified"."

The issue of "understanding", which historically was often connected with our ability to predict a systems behavior, has become a more subtle issue, with the advent of computer "reconstruction" methods, artificial neural networks, and the like. This area needs a lot of reflection. In any case, Weisskopf has raised a number of important points about the relationship of "parts" and the "whole" at steps of any hierarchy, which require clarification.

Ernst Mayr

It is valuable to benefit from some of the insights about science, and reductionism in particular, as viewed by scientists other than physicists. What follows is a brief excerpt from E. Mayr's book on biological thoughts [15], giving his views about three forms of reductionism. This discussion of different types of reductionism is not very common, and hence of considerable importance in formulating new ideas for the future. Other references to his thoughts in these matters can be found in [16]. Mayr has characterized Weinberg as "a horrible example of the way physicists think", and "an uncompromising reductionist" [17] - as Weinberg himself pointed out [18]. In light of recent clarification by Weinberg, to be noted below, one may assess whether there is any grounds for agreement in the future! Now for a biologist's perspective, I paraphrase from Mayr [15]:

"**Constitutive Reductionism**

It asserts that the material composition of organisms is exactly the same as that found in the inorganic world. Furthermore, it posits that none of the events and processes encountered in the world of living organisms is in any conflict with the physio-chemical phenomena at the level of atoms and molecules.... Virtually all biologists accept the assertions of constitutive reductionism, and have done so (except the vitalists) for the last two hundred years or more....

Explanatory Reductionism

This type of reductionism claims that one cannot understand a whole until one has dissected it into its components, and again these components into their components, down to the lowest hierarchical level of integration. In biological phenomena it would mean reducing the study of all phenomena to the molecular level, that is, 'Molecular biology is all of biology.... explanatory reductionism is sometimes illuminating. The function of the genes was not understood until Watson and Crick had figured out the structure of DNA. In physiology, likewise, the functioning of an organism is usually not fully understood until the molecular processes at the cellular level are clarified....(but) processes at the higher hierarchical level are often largely independent of those at the lower levels. The units of the lower levels may be integrated so completely that they operate as units of the higher levels. The functioning of articulation (motion of joints) can be explained without a knowledge of the chemical composition of the cartilage. Furthermore, replacing the articulating surface with a plastic... may completely restore the normal functioning of an articulation.... A facile application of explanatory reductionism can do more harm than good- early cell theory interpreted an organism as "an aggregate of cells", early population genetics considered the genotype to be an aggregate of independent genes with constant fitness values.

Theory reductionism

This type of reductionism postulates that the theories and laws formulated in one field of science (usually a more complex field or one higher in the hierarchy) can be shown to be special cases of theories and laws formulated in some other branch of science. If this is done successfully, one branch of science has been "reduced" to the other one, in the quaint language of certain philosophers of science. To take a specific case, biology is considered to be reduced to physics when the terms of biology are defined in terms of physics and the laws of biology are deduced from the laws of physics.

... I am not aware of any biological theory that has ever been reduced to a physio- chemical theory.... Theory reductionism is a fallacy because it confuses process and concepts.... such biological processes as meiosis, gastrulation, and predation are also chemical and physical process, but they are only biological concepts and cannot be reduced to physio-chemical concepts.... Species,

> competition, territory, migration and hibernation are examples of organismic phenomena for which a purely physical description is at best incomplete and usually biologically irrelevant."

Mayr's book [15] also contains an interesting chapter 'The Place of Biology in the Sciences', which gives an entirely different perspective of science from the ones presented by most physicists. A basic requirement of the developing metamorphosis of science will be to resolve these visions of science.

It is important also to factor in such considerations as Mayr's reaction to Weisskopf's article [14]

> "Even V. Weisskopf, normally quite free of the usual hubris of the physicists, forgot himself recently sufficiently to claim that 'the scientific world view is based upon the great discoveries of the nineteenth century concerning the nature of electricity and heat and the existence of atoms and molecules' (14:p. 405), as if Darwin, Bernard, Mendel, and Freud (not to mention hundreds of other biologists) had not made a tremendous contribution to our scientific world view, indeed, perhaps a greater one that the physicists."

Next I will turn to the extensive writings of Weinberg, and begin with his reaction to Mayr's categorizations of reductionism. One will see immediately the great difference that the term "reduction" can mean to two eminent scientists.

Steven Weinberg

Reading from Steven Weinberg's extensive writings can produce a variety of reactions, for his messages are often simultaneously interesting, provocative, obtuse, and occasionally apparently inconsistent in their inter-relations. I will attempt to present some flavor of this spectrum in what follows.

Let me begin with Weinberg's reaction to Mayr's categories of reductionism, presented above. It will be immediately clear from this that Weinberg has an entirely different agenda from Mayr's, and much of science, when it comes to "reductionism", and this will be born out in detail as we proceed. First, Weinberg says about Mayr's categories [18: p. 60]:

> "The main reason I reject this categorization is that none of these categories has much to do with what I am talking about (though I suppose theory reductionism comes closest). Each of these three categories is defined by what scientists actually do or have done or could do; I am talking about nature itself. For instance, even though physicists cannot actually explain the properties of very complicated molecules like DNA in terms of the quantum mechanics of electrons, nuclei, and electric forces, and even though chemistry survives to deal with such problems with its own language and concepts, still there are no autonomous principles of chemistry that are simply independent truths, not resting on deeper principles of physics."

Concisely put, Weinberg is "talking about nature itself....independent truths, not resting on deeper principles of physics", and not about what "scientists actually do or have done or could do". What follows is an elaboration of Weinberg's distinction, and his attempt to "join" them in some fashion (after all, "what scientists actually do" is the present basis for scientific knowledge, so if this is to be extended, some "join" must be accomplished.)

As examples of Weinberg's more reductive pronouncements (using the "in principle" principle) [19]:

> "Newton's dream, as I see it, is to understand all of nature, in the way that he was able to understand the solar system, through principles of physics that could be expressed mathematically. That would lead through the operation of mathematical reasoning to predictions which should in principle be capable of accounting for everything...."
>
> "The goal is the formulation of a few simple principles that explain why everything is the way it is. This is Newton's dream and it is our dream...."

¿From here he appears to make an indefensible evaluation:

> "We are interested in the final principles that we hope we will learn about by studying these [elementary] particles. So the first lesson is that the ordinary world is not a very good guide to what is important....".

But then he clarifies this, for his "final answer", of course:

> "... the importance of phenomena in everyday life is, for us, a very bad guide to their importance in the final answer."

In another extensive article [20] Weinberg wrote, in defense of attacks on reductionism:

> " ... in their attacks on reductionism ...(they are) missing the point. In fact, we all do have a sense that there are different levels of fundamentalness.... We do have the feeling that DNA is fundamental to biology. It's not that it's needed to explain transmission genetics, and it's certainly not needed to explain human behavior, but DNA is fundamental nonetheless. What is it then about the discovery of DNA that was fundamental to biology? And what is it about particle physics that is fundamental to everything?"

This "everything" does get tiresome. His inward-bound focus is exemplified by:

> "In all branches of science we try to discover generalizations about nature, and having discovered them we always ask why they are true. I don't mean why we believe they are true, but why they are true. Why is nature that way? When we answer this question the answer is always found partly in contingencies, that is, partly in just the nature of the problem we pose, but partly in other generalizations. And so there is a sense of direction in science, that some generalizations are 'explained' by others."

The fundamental significance of these "contingencies" (constraints), which always have to be specified for any physical phenomena, will be discussed more later.

In a recent review article [21], Weinberg did not distinguish himself by introducing the characterization of "grand and petty reductionism". However, he made very clear that "grand" reductionism has nothing to do with understanding the world around us, but is simply a matter of faith. It is "the view that all of nature is the way it is... because of simple universal laws, to which all other scientific laws may in some sense be reduced".

So this view, which envisions a reduction of all other scientific laws "in some sense", is what he considers to be "grand". By contrast, "petty reductionism is the much less interesting doctrine that things behave the way they do because of the properties of their constituents". This, again, evades the basic issue of what the "properties" may be all about.

The very important point is to understand Weinberg's distinction "between reductionism as a program for scientific research and reductionism as a view of nature." In other writings he stated this in the form "now reductionism ... is not a fact about scientific programmes, but is a fact about nature ... not the future organization of the human scientific enterprise, but an order inherent in nature itself". He feels that "much of the criticism of [his] reductionism is really only criticism of reductionism as a program for research." I think that that is an important point to understand in searching for the future transformation of scientific thought.

Indeed, I think that the clarification of this point can serve as a foundation for both eliminating misunderstandings, which are often the cause of more emotional than intellectual responses, and restructuring a unifying program for all of Science - which I will discuss in the next section.

The nonconstructive character of this faith is illustrated by:

> "...we understand perfectly well that hydrodynamics and thermodynamics are what they are because of the principles of microscopic physics. No one thinks that the phenomena of phase transitions and chaos ... could have been understood on the basis of atomic physics without creative new scientific ideas, but does anyone doubt that real materials exhibit these phenomena because of the properties of the particles of which the materials are composed?"

Then one finds that Weinberg candidly points out difficulties in his metaphysical stance:

> "Another complication in trying to pin down the elusive concept of 'explanation' is that very often the 'explanations' are only in principle.... we also would say that a chemical behavior, the way molecules behave chemically, is explained by quantum mechanics and Coulomb's law, but we don't really deduce chemical behavior for very complex molecules that way.... In this case

> we can at least fall back on the remark that ... we could if we wanted to. We have an algorithm, the variational principle, which is capable of allowing us to calculate anything in chemistry as long as we had a big enough computer and were willing to wait long enough."

This contention about computational capabilities is quite erroneous for most cases, because we do not have the algorithm relevant to our observables of interest (to be discussed in the next section). This he also recognizes, when the issues are closer to his field of interest:

> "The meaning of 'explanation' is even less clear in the case of nuclear behavior. No one knows how to calculate the spectrum of the iron nucleus, or the way the uranium nucleus behaves when fissioning, from quantum chromodynamics. We don't even have an algorithm.... Nevertheless, most of us are convinced that quantum chromodynamics does explain the way nuclei behave. We say it explains 'in principle', but I am not really sure of what we mean by that."

But then he partially recovers:

> "Still, relying on this intuitive idea that different scientific generalizations explain others, we have a sense of direction in science. There are arrows of scientific explanation, that thread through the space of all scientific generalizations.... These arrows seem to converge to a common source! Start anywhere in science and, like an unpleasant child, keep asking "Why?". You will eventually get down to the level of the very small."

followed by uncertainty:

> "...sometimes it isn't so clear which way the arrows of explanation point."

The above question, "why ?", is always a reductionistic question. As Weinberg noted, it does not involve such questions as "why does a fluid form vortices behind an obstacle?" or "why do evolutionary processes develop along certain lines?", or "why do we see images, or hear sounds?" These, and endless other questions, do not yield an arrow to the level of the very small. They do, sometimes, lead to a "smaller" level than that used for the gross description of the phenomena (to "see" or "hear sound" requires some reduction, but the fluid equations are the most reduced theory that gives any hope of "explaining" vortex formation). There is a level of reductionism beyond which a theory fails to predict or reproduce the original phenomenon, and hence to "explain" it in any acceptable sense.

Weinberg, for all of his apparently strongly reductionistic beliefs, frankly characterizes himself as "a compromising reductionist". Illustrating this position, he wrote:

> "...the notion that the other sciences will eventually lose their identity and all be absorbed into elementary particle physics; they will all be seen as just branches of elementary particle physics ... I certainly don't believe that. Even within physics itself, leaving aside biology, we certainly don't look forward to the extinction of thermodynamics and hydrodynamics as separate sciences; we don't even imagine that they are going to be reduced to molecular physics, much less to elementary particle physics."

Nonetheless, he went on to remark:

> "...we understand perfectly well that hydrodynamics and thermodynamics are what they are because of the principles of microscopic physics. No one thinks that the phenomena of phase transitions and chaos ... could have been understood on the basis of atomic physics without creative new scientific ideas, but does anyone doubt that real materials exhibit these phenomena because of the properties of the particles of which the materials are composed?"

Some may marvel as to why 'we understand perfectly well', based on some 'principles' and 'properties' never empirically substantiated in the lower-energy, OB domain. Overlooking this element of faith, one sees that he certainly appreciates that these phenomena required "creative new scientific ideas". Thus, for a constructive vision of Science, "creative new scientific ideas" will always be needed. This realization is the beginning of a transformation of "metaphysics" to a constructive process, to be pursued in the next section.

To further explain his position, he continued:

> "Now reductionism ... is not a fact about scientific programmes, but is a fact about nature .... I would call it objective reductionism.... I wish to emphasize that what I am talking about here is not the future organization of the human scientific enterprise, but an order inherent in nature itself."

Despite this, Weinberg felt that it was possible to argue before Congress for the construction of the 4.4 billion dollar superconducting supercollider, on the grounds that particle physics "...is in some sense more fundamental than other areas of physics", even though "the future organization of the human scientific enterprise" is not related to this 'fundamentalism'. Thus society is being asked to support, instead of the future organization of science, an "in-some-sense" fundamentalism, which is to say, a faith that is akin to Einstein's "cosmic religious feeling". It is certainly one of Weinberg's least defensible positions.

However, on balance, I think that Weinberg's struggle to explain his position, interjected as it is with honest uncertainties and problems, is of considerable value in the search for some standard set of principles, which can be used to generate scientific understandings in all fields of Science. Hence, for use in the next section, let me distill from these statements by Weinberg the following issues that he raised:

> (W1) His grand reductionism (GR) refers to "an order inherent in nature itself" and not to "the future organization of the human scientific enterprise". On the one hand, it is a research program, searching for *one* particular order in nature at high energies. On the other hand, GR involves a statement of his faith that "the simple universal laws" (if they exist) can be viewed as "fundamental to everything", and that, "in principle", they will explain "why everything is the way it is", because "all other scientific laws may in some sense be reduced" to these universal laws.

(W2) He recognizes that when we ask "Why is nature that way?", then the answer "is always found partly in contingencies, that is, partly in just the nature of the problem we pose, but partly in other generalizations."

(W3) He acknowledges that certain phenomena could not "have been understood on the basis of atomic physics without creative new scientific ideas..."

I suggest that, as a research program, (W1) is an important branch of science; as a statement of faith, it is not relevant to the understanding of any phenomena outside of the high-energy domain. However, I think that, in his "contingencies" observations (W2), and "new scientific ideas" in (W3), he touched upon some essential points, which require future exploration (next section).. for the future. I will return to these in the next section.

Stephen Hawking

Stephen Hawking has written a book [1], in which he makes some sweeping pronouncements about the goals of his scientific efforts. As noted by Carl Sagan in the introduction of this book, "This is also a book about God ... or perhaps about the absence of God. The word God fills these pages. Hawking embarks on a quest to answer Einstein's famous question about whether God had any choice in creating the universe. Hawking is attempting, as he explicitly states, to understand the mind of God.....[in his] effort, at least so far...[he has found] nothing for the Creator to do".

As an indication of the depths of Hawking's association with God, one notes that, toward the end of their twenty-five years of marriage, in 1990, Jane Hawking remarked that her role in Hawking's life had changed; it was no longer to encourage a sick husband, it was "simply to tell him that he's not God". [22]

For all his mathematical brilliance, he associates his Godly quest with the unidirectional, inward-bound vision of science, in a fashion that sheds little light on most of the interests of science. His view is entirely different from Feynman's: "I do not think either end is nearer to God.", quoted above. And, in contrast with even the "compromising reductionist" Weinberg, Hawking makes no acknowledgments in his book of "contingencies", or the need for "new scientific ideas" to understand the more complicated phenomena in nature.

Among his more interesting general observations about science is his fundamental paradox [1:p. 12]:

> "Now, if you believe that the universe is not arbitrary, but is governed by definite laws, you ultimately have to combine the partial theories into a complete unified theory that will describe everything in the universe. But there is a fundamental paradox in the search for such a complete unified theory. The ideas about scientific theories outlined above assume we are rational beings who are free to observe the universe as we want and to draw logical deductions from what we see. In such a scheme it is reasonable to suppose that we might progress ever closer toward the laws that govern our universe. Yet if there really is a complete unified theory, it would also presumably determine our

> actions. And so the theory itself would determine the outcome of our search for it! And why should it determine that we come to the right conclusions from the evidence? Might it not equally well determine that we draw the wrong conclusions? Or no conclusion at all?
>
> The only answer that I can give to this problem is based on Darwin's principle of natural selection. The ideas is that in any population of self-reproducing organisms, there will be variations in the genetic material and upbringing that different individuals have. These differences will mean that some individuals are better able than others to draw the right conclusions about the world around them and to act accordingly.... our scientific discoveries may well destroy us all, and even if they don't, a complete unified theory many not make much difference to our chances of survival. However, provided the universe has evolved in a regular way, we might expect that the reasoning abilities that natural selection has given us would be valid also in our search for a complete unified theory, and so would not lead us to the wrong conclusions.
>
> Because the partial theories that we already have are sufficient to make predictions in all but the most extreme situations, the search for the ultimate theory of the universe seems difficult to justify on practical grounds.... The discovery of a complete unified theory, therefore, may not aid the survival of our species. It may not even affect our life-style. But ever since the dawn of civilization, people have not been content to see events as unconnected and inexplicable. They have craved an understanding of the underlying order in the world. Today we still yearn to know why we are here and where we came from. Humanities deepest desire for knowledge is justification enough for our continuing quest. And our goal is nothing less than a complete description of the universe we live in."

It is rather amazing on the one hand to present such a basic paradox, and then to proceed to largely ignore it; a superb example of his faith, stated clearly in the first and last sentences above.

In the following, one sees Hawking's faith in pushing through mathematical deductions of everything [1:p. 167]:

> "What would it mean if we actually did discover the ultimate theory of the universe? ...we could never be quite sure that we had indeed found the correct theory, since theories can't be proved. But if the theory was mathematically consistent and always gave predictions that agreed with observations, we could be reasonably confident that it was the right one.... Even if we do discover a complete unified theory, it would not mean that we would be able to predict events in general, for two reasons. The first is the limitation that the uncertainty principle of quantum mechanics sets on our powers of prediction.... In practice, however, this first limitation is less restrictive that the second one. It arises from the fact that we could not solve the equations of the theory exactly, except in very simple situations. (We cannot even solve exactly for

the motion of three bodies in Newton's theory of gravity, and the difficulty increases with the number of bodies and the complexity of the theory.) We already know the laws that govern the behavior of matter under all but the most extreme conditions. In particular, we know the basic laws that underlie all of chemistry and biology. Yet we have certainly not reduced these subjects to the status of solved problems .... So even if we do find a complete set of basic laws, there will still be in the years ahead the intellectually challenging task of developing better approximation methods, so that we can make useful predictions of the probable outcomes in complicated and realistic situations. A complete, consistent, unified theory is only the first step: our goal is a complete understanding of the events around us, and of our own existence."

We have known enough about the problem of three gravitating bodies for a half century, to know that the issues are much more profound than simply an "intellectually challenging task of developing better approximation methods". As an example, discussed in section 5, Duhem pointed out in 1906 that there are solutions which can never be relevant to physical observations. The general issue of connecting mathematical predictions with experimental observations does not seem to be of great concern to Hawking. Likewise, they were apparently not of great interest to Einstein in his later years [7:p.45].

As with many modern scientists who have been focused on quantum mechanical effects, Hawking completely misses the future "task of science" in his pronouncement:

> "In effect, we have redefined the task of science to be the discovery of laws that will enable us to predict events up to the limits set by the uncertainty principle"[16].

As will be discussed in the next section, there are many more important sources of uncertainty in understanding nature than the quantum mechanical uncertainty principle - and they are just as fundamental!

He ends this book with his ultimate vision of faith [1:p.157]:

> "However, if we do discover a complete theory, it should in time be understandable in broad principle by everyone, not just a few scientists. Then we shall all, philosophers, scientists, and just ordinary people, be able to take part in the discussion of the question of why it is that we and the universe exist. If we find the answer to that, it would be the ultimate triumph of human reason - for then we would know the mind of God."

In the next section, we will contrast this metaphysical faith with a constructionist form of "metascience".

Anthony Leggett

A. J. Leggett is a member of the small group of physicists who have drawn attention to the limitations of our knowledge, based on the inward-bound reduction program. He has discussed many of these issues in his fine book concerning problems in physics [23], from which the following quotations are drawn.

A basic (implied) assumption, contained in the terminology "fundamental laws", is that those very limited relationships found in high-energy scattering interactions can in fact explain all of the behavoirs in nature.

In connection with the general issue of claiming knowledge far from the sources of empirical information, Leggett said [p. 175]:

> "For a physicist to claim that he "knows" with certainty exactly how a particular physical system will behave under conditions very far from those under which it has been tested ... seems to me arrogant".

However, he also offered the following rationale for allowing some "extensions" [p. 176]:

> "Let me now return to the claim that 'the four basic interactions ... together with cosmology, account for all known natural phenomena'. This is, of course, not a statement of fact, but an act of faith. It is not an unreasonable one. What anyone who makes it is saying, in effect, is that while there are many natural phenomena which currently have not actually been explained in detail in terms of the four basic interactions, there is no clear example at present of a single phenomenon which we can prove cannot be so explained; so that the principle of Occam's razor suggests that we should try to get along with the interactions we know about."

This, at best, is quite misleading. As has been discussed in section 5, the three-body problems generally 'cannot be so explained', and this can be proved (that is, there are physical questions, of basic and general interest, which can be proved not to have mathematical answers from Newton's theory). Moreover, the fact that one can not prove that something can not be disproved, hardly establishes the latter. In fact Leggett is one of the very few to point out some of these interaction issues, as will be discussed shortly. So one certainly can wonder what it means to 'get along with the interactions we know about'. We can't 'get along' very far, as Leggett himself clearly noted in this very important discussion [p. 177]:

> "A question which I personally find even more fascinating is this: Is the behavior of complex systems indeed simply a consequence of the 'complex interplay among many atoms, about which Heisenberg and his friends taught us all we need to know long ago'.... Or does the mere presence of complexity or organization or some related quality introduce new physical laws? To put it another way, would the complete solution of the basic equations of quantum mechanics - Schrödinger's equation - for, say, the 10^{16} - odd nuclei and electrons composing a small biological organism actually give us, were it achievable, a complete description of the physical behavior of such an organism? The convention answer to the question is undoubtedly yes. But what few people realize is the flimsiness - or rather, the complete absence - of positive experimental evidence for this conclusion. It is indeed true that application of the formalism of

quantum mechanics to complex systems yields predictions for currently measurable quantities which are often in good agreement, quantitatively as well as qualitatively, with the experimental results; and that in cases where there is substantial disagreement, there are usually enough unknown factors in the experimental system or approximations in the theory that the discrepancy can be plausibly blamed on one or the other or a combination thereof."

One might interject here that it is not only the absence of experimental evidence, but also any rigorous mathematical evidence relate to it. A very important point is raised here, which we needs to be returned, is the characterization of "approximations in the theory". What this, in fact, nearly always amounts to is the introduction of an entirely new theory (a new inductive process is involved, which, while "reasonable" has no deductive connection with the original theory. This is partially reflected as Leggett continues, with further important remarks in connection with quantum mechanics [p. 177]:

> "Certainly there is at present no clear evidence that such quantum-mechanical calculations give the wrong answers. What is rarely appreciated, however, is that, in the context of meaningful tests of quantum mechanics, in almost all cases up till now one has been dealing with very 'crude' features, which are in some sense the sum of one-particle (or 'one-quasi-particle') properties, or at best properties of pairs of particles. Where the specifically quantum-mechanical aspects of the behavior of a complex system can indeed be regarded as effectively the sum of the contributions of such small groups of microscopic entities, quantum mechanics seems to work well. Beyond this,..., it has barely begun to be genuinely tested."

And, in his notes [p. 183]

> "Even the phenomena of superfluidity and superconductivity, spectacular as they are, are still in the relevant sense the sum of a large number of one- or two- particle effects."

I believe that the "quasi-particle" characterizations raised here (and in other contexts, "collective variables") are but part of a much larger mode of understanding complex phenomena in all systems; involving "ensemble variables", to be discussed in the next section.

As to the "fundamental" character of the present quantum laws, as they relate to our understanding common physical phenomena, Leggett offered these thoughts [pp. 178-9]:

> "I am personally convinced that the problem of making a consistent and philosophically acceptable 'join' between the quantum formalism which has been so spectacularly successful at the atomic and subatomic level and the 'realistic' classical concepts we employ in everyday life can have no solution within our current conceptual framework."

Leo Kadanoff

In contrast to the other scientists quoted here, Leo Kadanoff was one of the few renowned physicists to have done extensive research in the area of nonlinear, complex dynamics. His insights on the changing character of physics therefore both carry authority and uniqueness to many of these issues. Here are some of his remarks, and note that his use of "reduction" is akin to Weinberg's "grand reduction" [24]:

> "In recent years there has been some change in the attitude of many physicists toward complexity.... Physicists have begun to realize that complex systems might have their own laws, and that these laws might be as simple, as fundamental, and as beautiful as any other laws of nature. Hence, more and more the attention of physicists has turned toward nature's more complex and "chaotic" manifestations, and to the attempt to construct laws for this chaos.... the concentration upon chaos has been a part of a change in our understanding of what it means for a law to be "fundamental" or "basic". Physical scientists have sometimes been tempted to take a reductionist view of nature. In this view, there are fundamental laws and everything else follows directly and immediately from them. Following this line of thought, one would construct a hierarchy of scientific problems. The "deepest" problems would be those connected with the most fundamental things, perhaps the largest issues of cosmology, or the hardest problems of mathematical logic, or maybe the physics of the very smallest observable units in the universe. To the reductionist the important problem is to understand these deepest matters and to build from them, in a step-by-step way, explanations of all other observable phenomena."
>
> "Here I wish to argue against the reductionist prejudice. It seems to me that considerable experience has been developed to show that there are levels of aggregation that represent the natural subject areas of different groups of scientists. Thus, one group may study quarks (a variety of subnuclear particle), another, atomic nuclei, another, atoms, another molecular biology, and another, genetics. In this list, each succeeding part is made up of objects from the preceding level. Each level might be considered to be less fundamental than the one preceding it in the list. But at each level there are new and exciting valid generalizations which could not in any very natural way have been deduced from any more "basic" sciences. Starting from the "least fundamental" and going backward on the list, we can enumerate, in succession, representative and important conclusions from each of these sciences, as Mendelian inheritance, the double helix, quantum mechanics, and nuclear fission. Which is the most fundamental, the most basic? Which was derived from which? from this example, it seems rather foolish to think about a hierarchy of scientific knowledge. Rather, it would appear that grand ideas appear at any level of generalization."

In further writing about complexity, he addressed "fundamental" issues [25] In an article in 1987, he wrote:

> "The astrophysicist, who must understand the distribution of matter in the distribution of matter in the universe; the biophysicist, asking perhaps how life arose; the plasma physicist, working with the intertwined structure of flux lines in a swirling ionized gas; the solid-state scientist, looking at the crystallization of a piece of steel - all these scientists must deal with complexity as an everyday issue. Until recently, many physicists have dismissed examples such as these as "dirt physics" or "squalid-state physics"- perhaps intending to suggest that these examples somehow contain less intellectual content than, say, a simple and easily interpreted spectrum. Here, I wish to suggest the possibility of the opposite view: that the observed complexity in the world around us raises questions that are absolutely fundamental to our understanding of the nature of physical law. Three such questions are:
>
>> How do very simple laws give rise to richly intricate structures?
>>
>> Way are such structures so ubiquitous in the observed world?
>>
>> Why is that these structures often embody their own kind of simple physical laws? "

Note that these questions only focus on structure; but clearly they can, and should be, extended to concepts of dynamic processes, including adaptive and functional aspects, which are generally most important in nature.

Murray Gell-Mann

While Murray Gell-Mann is well-known as a Noble Laureate in high-energy physics, and the inventor of the quark, his interests and expertise spreads out in many other directions. Some examples of this can be found in his far-ranging book, The Quark and the Jaguar.[mg1] While this contains many interesting insights, his knowledge and understanding of dynamic concepts is limited, and fails to reflect some important concepts in the unfolding metamorphosis of science. The purpose of this section is not to detail such technical matters, but a few examples may not be inappropriate at this point.

He suggests that chaos could act as "a mechanism that can amplify to macroscopic levels the indeterminacy inherent in quantum mechanics"[26,p.27]. While this might be the case, and might play a role in some cognitive functions, it is quite clear that the most generic influence of chaos lies in its direct impact on macroscopic phenomena (including cognitive processes, of course). And while it has been clear for some time that deterministic chaos sheds no light on financial market fluctuations, as has been recently publicly confirmed [27], Gell-Mann succumbed to some public-relations hyperbole [28] in his account of the significance of chaotic dynamics in these markets [26,p.48]. Also one finds the "in-principle" principle generously applied in justifying the importance of QED in our everyday world. In two pages of discussion [26,pp. 110-111] we are assured of this importance by five "in-principle" exhortations. Nonetheless, this book contains valuable insights, and testifies to the sensitivity that this renowned high-energy physicist has brought to the search for an understanding of emergent phenomena in complex systems.

What is particularly impressive, and indeed highly significant in any attempt to join the understandings developed by high-energy research with the central areas of future scientific research, is Gell-Mann's recent overview of this topic [29]. I think that this makes a very significant contribution to furthering the metamorphosis of science. He certainly has given one of the most eloquent and insightful discussions of the marriage of high-energy physics with hierarchical issues and the associated concept of emergence. What follows are some quotations from this important article:

> "In my opinion, a great deal of confusion can be avoided, in many different contexts, by making use of the notion of emergence. Some people may ask, 'Doesn't life on Earth somehow involve more that physics and chemistry plus the results of chance events in the history of the planet and the course of biological evolution? Doesn't mind, including consciousness or self-awareness, somehow involve more than neurobiology and the accidents of primate evolution? Doesn't there have to be something more?' But they are not taking sufficiently into account the possibility of emergence."
>
> "Life can perfectly well emerge from the laws of physics plus accidents, and mind, from neurobiology. It is not necessary to assume additional mechanisms or hidden causes."

The following two enigmatic sentences are particularly interesting:

> "Once emergence is considered, a huge burden is lifted from the inquiring mind. We don't need something more in order to get something more."
>
> "Although the 'reduction' of one level of organization to a previous one - plus specific circumstances arising from historical accidents - is possible in principle, it is not by itself an adequate strategy for understanding the world. At each level new laws emerge that should be studied for themselves; new phenomena appear that should be appreciated and valued at their own level.
>
> It in no way diminishes the importance of the chemical bond to know that it arises from quantum mechanics, electromagnetism, and the prevalence of temperatures and pressures that allow atoms and molecules to exist. Similarly, it does not diminish the significance of life on Earth to know that it emerged from physics and chemistry and the special historical circumstances permitting the chemical reactions to proceed that produced the ancestral life form and thus initiated biological evolution. Finally, it does not detract from the achievements of the human race, including the triumphs of the human intellect and the glorious works of art that have been produced for tens of thousands of years, to know that our intelligence and self-awareness, greater than those of the other animals, have emerged from the laws of biology plus specific accidents of hominid evolution."

Gell-Mann ends eloquently with:

"When we human beings experience awe in the face of the splendors of nature, when we show love for one another, and when we care for our most distant relatives - the other organisms with which we share the biosphere - we are exhibiting aspects of the human condition that are no less wonderful for being emergent phenomena."

In this article Gell-Mann focuses strongly on the concept of "emergence", without much specificity. He feels that "Although the 'reduction' of one level of organization to a previous one - plus specific circumstances arising from historical accidents - is possible in principle, it is not by itself an adequate strategy for understanding the world.", which seems to require a new, undefined strategy to make scientific progress. Instead he offers "At each level new laws emerge that should be studied for themselves; new phenomena appear that should be appreciated and valued at their own level." How these laws are to emerge, and be related to others at a "previous" level, without an "adequate strategy" in place is unclear. Nonetheless he feels that, somehow, a "huge burden is lifted from the inquiring mind", and that we "don't need something more in order to get something more".

I believe that Gell-Mann's emphasis of "emergence", "historical accidents", or better yet "historical circumstances", and "the 'reduction' of one level of organization to a previous one", are some of the parts of a fairly coherent future "adequate strategy" for the development of all natural/social sciences, and, most importantly, sans "in principle". This will be developed in the next section.

Finally, there are many other interesting and important "metaphysical" discussions by other modern scientists, which are not included in this section [30]. Some of their thoughts, and those of others, will be referred to in the next section.

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[3] A. Einstein, Ideas & Opinions (Bonanza Books, NY.), p. 233

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[19] S. Weinberg, Newton's Dream, pp. 96-106 in "Newton's Dream" (M. S. Stayer, Ed.; Queen's Quarterly, McGill-Queen's Univ. Press, 1988)

[20] S. Weinberg, Newtonianism, Reductionism and the Art of Congressional Testimony", Nature 330, 433-437, Dec. 3 1987.

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[27] Joe Kolman (Ed.), "The World According to Norman Packard", Derivatives Strategy, pp. 30-34, December/January 1996

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S. Diner, A Renewal of Mechanism: Toward an Instrumental Realism, pp. 273- 284 in Dynamical Systems, A Renewal of Mechanism: centennial of David Birkhoff (S. Diner, D. Fargue, G. Lochak, Eds., World Scientific, 1986)

7 Transforming Component (III):

A "scaffolding metascience"; varieties of hierarchies; systems; constraints ensemble variables, correlates; Implicit and Explicit Orders, emergence; Bilevel reduction/synthesis; scientific uncertainties; dynamic universalities; the coupled universe; the East-West conjunction of Science; "Yin-Yang" aspects of Science; inherent limitations to scientific knowledge

This section has developed into something of a potpourri of ideas, all related to the changing character of our understanding of natural phenomena. A number of these ideas hang together with some cohesion, while others are rather disjoint observations. Hopefully, these will ultimately contribute to this ongoing transformation of our understanding of the unity of Science.

It is clear from the quotations in the last section that we have some distance to go in reaching this new unifying vision of Science. These quotations illustrate the wide diversity of views about the basis upon which to organize a general approach to scientific knowledge (understanding). However, even within this great diversity, it seems fair to say that, aside from some fringe elements of "microreductionists" (Hawking?), there are no scientists within the inward- bound (IB) group who claim that any of the more complex natural phenomena will ever be explained by an actual (logically) deductive process, beginning from some irreducible set of laws of nature (this appears to be one place Weinberg is willing to "compromise"). The trouble is that it often sounds as if they are essentially saying this, when they make some "in principle" statement, and this in turn generates strong reactions from some scientists. The IB scientists do indeed often vacillate on this issue, but most sense that the pure deductive process is a dead (or, they might prefer, irrelevant) issue. On the other hand, the OB scientists are quite convinced that this deductive ladder of knowledge is impossible, but rarely give substantial reasons for this belief. It is somehow simply all quite obvious to them, but never really nailed down with specifics. Therefore a basic division still remains, and this needs to be addressed in the process of transforming the component (III) in the foundations of Science.

What is involved here is the beginning of a major change in scientists' perceptions of their ability to understand Nature. While the Judeo-Christian cultures were based on the monotheistic image of God-given natural laws, which prescribed the moral principles for relationships among people, the concept of laws of Nature, involving the behavior of inanimate objects, only became firmly rooted with the writings of Descartes, Boyle, and Newton. Thus Descartes, in his Discours de la Méthode (1637), speaks of "laws which God has put into Nature", whereas Newton concludes his Principia Philosophiae (1644) by saying that it describes "what must follow from the mutual impact of bodies according to mechanical laws, confirmed by certain and everyday experiments." Paradoxically, Kepler never referred to his famous three laws of planetary motion as "laws" - the third law he referred to as a "theorem". Thus, one of the transformations that took place during the first metamorphosis of science was the firm establishment of the concept of God-given laws of Nature. An extensive discussion of the history of the concept of laws of nature has been given by Joseph Needham [1].

In this century, particularly with Einstein's development of the general theory of relativity, the more specific issue has been raised, as to whether physicists might be able to actually discover these "fundamental laws", which would explain everything; uncovering the mind of God, and so forth [2]. The quotations in the last section accept not only the existence of such natural laws, but proclaim the vision of a cosmic-religious scientific agenda, to actually discover these laws. To quote Weinberg once again, "The goal is the formulation of a few simple principles that explain why everything is the way it is. This is Newton's dream and it is our dream." I think that it can be made quite clear why this is an empty dream, which can never (repeat, can never) be fulfilled by us humans. In the last section is was noted that Weinberg came to characterize this reductionism as "Grand Reductionism", which is the enterprise to determining the "order inherent in nature itself" - the "fundamental laws of nature." As will be made clear in this section, even if we know mathematical laws, this does not imply anything about how much we could understand about the order that such laws might imply - they may well contain implicit orders that we could never uncover - and this is not philosophy, but explicitly illustrated by many technical examples.

7.1 A "Scaffolding" Metascience

An essential point to emphasize is that we can fully believe that Nature is governed by some orderly principles, (certainly a basic tenet of scientific research), and at the same time not subscribe to the idea that we very limited human beings can ever discover such general guiding laws. Indeed, I claim that we would never know if we had them, for the same technical reasons to be discussed later.

In contrast to Weinberg's program, "Now reductionism... is not a fact about scientific programmes, but is a fact about nature.... what I am talking about here is not the future organization of the human scientific enterprise, but an order inherent in nature itself.", the really important challenge of Science is to see how we can develop precisely this new "scientific program ... for the future organization of the human scientific enterprise", given the fact that it will never be based on the knowledge of all-encompassing guiding laws, combined with some (even "in principle") deductive process. The "loss" of this dream of discovering the general guiding laws of nature, should be viewed positively, in the sense expressed by G. B. Shaw:

> "You have learnt something. That always feels at first as if you lost something." G. B. Shaw, Major Barbara, Act 3

It was a scientific illusion -

> "The great obstacle of man is the illusion of knowledge.... The great significance of the voyages of discovery was their discovery of ignorance." D.J. Boorstin [3]

I believe that, in this second metamorphosis, we are certainly on a such a voyage of discovery. These discoveries include inherent limitations in obtaining in obtaining information, and the human cognitive ability to "comprehend" limited amounts of information. Thus we are left with the challenge to search for new metaphysical principles, which can unify our approaches for understanding complicated natural phenomena.

First, it is essential in this process to redefine the concept of "metaphysics" to be much more focused on scientific knowledge than is contained in the general philosophical concept "that deals with first principles and seeks to explain the nature of being and reality (ontology) and the origin and structure of the universe (cosmology); it is closely associated with the study of the nature of knowledge (epistemology)". It is this epistemological concern which is most "closely associated" with scientific activities, meaning that it is constrained by technical activities that we use to acquire "scientific knowledge."

I suggest that we adopt the vision of metaphysics presented by E. Schrödinger [4]:

> "Metaphysics does not form part of the house of knowledge but is the scaffolding, without which further construction is impossible."

In other words, a scientifically meaningful "metaphysics" needs to be based closely enough on the scientific information that we can in reality acquire, to allow us to develop the new "scaffolds" to build the future houses of scientific knowledge. This scaffolding is the only form of metaphysics that is appropriate for Science. Adopting this viewpoint, it seems very appropriate to divorce this concept entirely from its irrelevant placement in Aristotle's works, and its misleading association with physics. I suggest that this concept be referred to as "metascience"; so that Schrödinger's characterization becomes:

> Metascience does not form part of the house of knowledge but is closely enough constrained by scientific conditions, that it can suggest "scaffolds" from which further construction is possible.
>
> Clearly, just like any scaffolding, it can only be used to build limited houses of (deductive) knowledge - it would be not only illusionary but divisive to return to the metaphysical vision of building "universal" houses of knowledge.

In this search for a new unifying metascience, it is essential to review some of the historic conceptual methods that have yielded progress in science. This includes not only physicists, but chemists, astronomers, fluid dynamicists, and ecologists. Particularly revealing are modern methods that have been used by OB physicists, in order to understand the more complex phenomena within the inanimate world. A study of their approach leads to a reformulation of an Einstein admonition:

> "If you want to find out anything from the theoretical physicists about the methods they use, I advise you to stick closely to one principle: Don't listen to their words, fix your attention on their deeds."

For the present purposes, this might be reformulate as:

"If you want to discover the metascience that has been developed by scientists, fix your attention on their accomplishments."

After one studies this issue for a while, it becomes clear that there is nothing particularly modern about this metascience - it only has become more spectacular and obvious during this century. To play this spectacular card, we will consider some of the accomplishments of the OB physicists to obtain some insights into what the metascience will involve. The "understanding" reached in more complex OB phenomena, exposes commonalities with historically simpler phenomena, which seem very likely to constitute part of any future metascience "understanding".

7.2 Various Hierarchies

At the heart of this "understanding", which has been developed, not just in physics, but in all branches of science, lies the recognition that there are various forms of "hierarchies" within nature - a rather flexible concept, as we will see. However, "understandings" have always relied upon making some connections between various "levels" within these hierarchies. This, of course, has led to one extreme view of "reductionism"; specifically, as advocated by those with the IB conception of understanding nature. As a part of someone's metaphysical belief and faith, this can not be challenged. It is their "cosmic religious feeling", to use Einstein's phrase, and religious beliefs are inviolate. However, as a component of a metascience, "reductionism" needs to be joined with "constructionism", to yield an operational "scaffolding" for the future construction of Science.

To keep some perspective in these matters, and to learn from the past, let us recall that hierarchical views of Nature are very ancient. They go back independently to Greece and China, in the 4th and 3rd century BC. This is discussed in Joseph Needham's wonderful book, Science and Civilisation, Vol. 2, section 9(e), Theories of the 'Ladder of Souls'[5]. The lesson to be learned here is conceptual - contrasting the perception of Nature from the rational viewpoint of Aristotle (-4th century), and the relational viewpoint of Hsün Chhing (-3rd century). Their respective hierarchies at this time were:

Aristotle: plants (vegetative soul) → animals (plus sensitive soul) → man (plus rational soul)

Hsün Chhing: water and fire (subtle spirit) → plants (plus life) → animals (plus perception) -¿ man (plus justice)

The distinctions are interesting, and particularly fundamental at the level of "man". The correlational viewpoint of the Chinese culture is quite evident, and distinct from the rational emphasis of Aristotle. I believe that there is more than history to be gleaned from this comparison; these two views can also jointly contribute to our modern metascience, as discussed later.

It should also be noted that in both of these views of a hierarchy, something is being added as one goes up each level; and that what is being added has nothing to do with any deductive process - it has to do with our perception of a new "constraint", or condition, that applies to the systems in the next level systems. The generality of such constraint conditions will be elaborated on shortly.

To broaden the possible future scope of this metascience, let's list only several of many possible types of hierarchies:

Structural Hierarchy:

elementary particles → atoms → molecules → macromolecules →
membranes → cells → nucleus, microsomes, mitochondria, etc.) →
organisms → multi-organism systems

Functional Hierarchy:

Inanimate Systems	→	Living Systems	→	Cognitive Systems	→	Introspective Systems	→	Social Systems

Dynamic Hierarchy:

Closed Systems	→	Open Passive Systems	→	Simple Adaptive Systems →
Complicate Adaptive Systems	→	Complex Adaptive Systems	→	Evolutionary Systems

Energetic Hierarchy	Temporal Hierarchy
(e.g., metastable ordering)	(e.g., particle, human,..., continental, solar, ... universe lifetimes)

In the temporal case, the conformational changes in macromolecules involve time scales roughly in the range 10^{-12} to 10^{-9} sec., whereas evolutionary and geological time scales range from 10^{12} to 10^{16} sec., or so. Similarly, we can break down length scales, from molecules, say 10^{-9} m, eucaryotic cells, around 10^{-5} m, island ecologies, maybe 10^{4} m, to planetary ecosystems, around 10^{7} m. All of these scales are important in defining the "systems" we are considering, which will be discussed shortly.

We can, of course, take many of these "systems" and break them down into their separate hierarchies, as Weisskopf explicitly did in the case of the structural hierarchy, into animate an inanimate hierarchies. However, these "macro- hierarchies" suffice to illustrate some of the varieties that exist. While "reductionism" is usually thought of in terms of the structural hierarchy, we obtain new perspectives on the needs of a metascience when we consider "understanding" within these other contexts. Nature is not one-dimensional in some hierarchical space.

7.3 Systems

In order to characterize any hierarchy, we need to take some care to define what we mean by a physical "system". Any "system" that we observe in Science will forever be only a small subsystem of our universe - it is characterized, in part, by what is in some finite region of space-time (both aspects being essential), *and*, very importantly, by the boundary conditions, which relates the system to the rest of the universe. "What is in some finite region of space-time" implies some constraints on the way the system was formed (how it got there), and on its environment, allowing it to exist for some "significant" duration of time (hence the temporal hierarchy).

The boundary conditions are essential in characterizing a system, as will be discussed in more detail shortly. For the present, I simply want to emphasize that an open system (see dynamic hierarchy), may involve matter, as well as energy and information, passing in and out of the "system" - it only being defined (generally) in terms of a finite region of space-time.

Even these "systems" contain much more information (from a microscopic viewpoint) than we can either obtain, or more importantly, comprehend. The human mind requires (necessitates) finite, in fact only "small amounts" of information within the "observables" that we extract (project) from these systems, if we have any hope of "understanding" the system (e.g., be able to discover some relationship between a set of observables). It is obviously impossible to be quantitative about this limitation, but it clearly exists. It is of some interest to note that Kolmogorov pointed out the usefulness of such a qualitative ordering of numbers in a related context [6].

7.4 The Dynamic Hierarchy

With this idea of a system, I will elaborate briefly on the concepts within the dynamic hierarchy above. I believe that this is particularly important, because dynamic processes form new "universalities" in Science, which are at least as important, and complimentary to the limited set of mathematical equations ("laws"), which historically were believed to express the only universal truths about nature. I believe that these views will change dramatically in the future (see "implicit" and "explicit" orders, below).

A "system" is now defined, in part, by whatever is in some finite region of space- time, *together* with boundary conditions indicating its (informational, functional, material, force) connections with the its "environment" (the rest of the universe). Then a "closed system" is one that has no connections to its environment - these are the systems we have most commonly study, and teach in school (e.g., the hallowed "Hamiltonian systems"). Open passive systems have a flux of some type (e.g., matter, force field, etc.) entering and leaving through a boundary (such as an electric current, and electric field, through a resistor) - clearly there is a lot implicit in this description, but the system doesn't change its "character or rules" due to the environment; it's "passive". The "simple adaptive" involves systems that change their dynamics (an "endo-dynamic" problem), in response to a change in the environment, possibly to allow the system to survive - e.g., metabolic problems. The "complicated adaptive" idea is where the system attempts to modify the environment for its advantage - e.g., the use of tools, putting on a coat, etc. - requiring some cognition, but on a "somewhat" passive environment (?). "Complex adaptive systems" are collections of adaptive systems, so their environment involves other adaptive systems - open to information, material, force fields, "functional", (etc?) fluxes through their boundaries. "Evolutionary systems" are complex adaptive systems that include the stochastic and cross-over genetic changes in their dynamic rules (this relates, of course, to distinguishing various dynamic time scales). Indeed there are clearly concepts of time-scale, energetic (metastability), and "functional" hierarchies which play important roles, along with these dynamic concepts. It's rather obvious that any reliance on a simple linear hierarchy is totally inadequate for understanding the wealth of natural wonders - but it helps to lay out a few such hierarchies, and consider how they may interweave with one another.

Starting from closed systems (hence inanimate), one frequently thinks of progressing up the dynamic levels by building not only on the laws of physics, but by some deductive processes from these laws and the material component parts. However, once we reach the arena that involves cognitive processes, it is very likely that quite different dynamic processes may require correspondingly very different dynamic modeling, if any scientific understanding is to be achieved. Complex adaptive systems, with their interactions of human cognitive processes, are the most complicated examples of this challenge. A very important contribution to the effort of obtaining a comprehensive approach to understanding complex adaptive systems, is the insightful book by John Holland, "Hidden Order" [7]. A great challenge for the future will be to see how his concepts can be related to other understandings of dynamic systems, which have been uncovered during the past century. Such a marriage of insights would certainly strengthen this metamorphosis.

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[2] M. Wertheim, "Quantum Mechanics and a "Theory of Everything" " In *Pythagoras' Trousers: God, Physics, and the Gender Wars*, Random House, Ch. 9, pp. 185-188, Times Books (1995)
S. W. Hawking, "A Brief History of Time", Bantam Books, (1988)

[3] D. J. Boorstin, "Discovery, Science, Technology, and the 'Illusion of Knowledge'" pg. 3, In *The Christian Science Monitor*, Peter Grier, ed. (1992)

[4] E. Schrödinger, "My View of the World" Ox Bow Press, Woodbridge, CT, (1983)

[5] J. Needham, "Theories of the 'Ladder of Souls' " In *History of Scientific Thought*, Vol. 2, Cambridge Univ. Press (1956)

[6] Ibid.

[7] J. H. Holland, "Hidden Order: How Adaptation Builds Complexity" Addison-Wesley (1995)

7.5 Ensemble Variables; Constraints; Nondeduction

This constraint on the informational content of our comprehensible "observables" led, since the time of Euler and Daniel Bernoulli, to the mathematization of the so-called "Eulerian variables", which appeared in their partial differential equations of fluid dynamics. Examples of such variables (observables?) are the density, $n(x,t)$, and flow velocity, $v(x,t)$, of a fluid. These variables are very different from the "Lagrangian variables" of ordinary differential equations, which are only dependent on time (t), rather than space and time, (x,t). The Lagrangian variables were the variables most commonly associated with Newtonian dynamics, but also Newton dealt with the effects of tides.

I do not know how Euler and Bernoulli conceptualized these "observables", but today we recognize them to be average quantities - that is, based on some average property of the molecules in the fluid, averaged over an "ensemble" of such systems all subject to some constraint (or assumed condition). The "ensemble" characterizes the probability of finding these molecules in different locations, and having different velocities, at some time, and we take the desired average over all these possible velocities to obtain the "ensemble variable", such as $n(x,t)$ and $v(x,t)$.

The physical constraints on the system is implicit in the particular ensemble that is used. For example, if the temperature is very high, the molecules are disassociated into atoms, which in turn may be ionized, in which case the ensemble must relate to the properties of such an ionized gas, and not to a liquid. Conversely, at lower temperatures, it must relate to some particular solid structure, and so on. The particular solid may depend on the history by which it was formed (e.g., the graphite, diamond, and Buckie-Ball forms of carbon solids). There is a lot of unknown history that goes into the present character of any physical system, and this is all implicitly captured in the ensembles we envision as representing that system.

One essential messages here are is that *all* of the systems of Science are characterized by us in terms of such ensemble variables (observables), and these are tied to constraints, and these are nondeducible:

systems	$\leftrightarrow$	**ensemble variables (observables)**	$\leftrightarrow$	**present/historical constraints**	$\leftrightarrow$	**unknown, nondeductive conditions**

Of course, we most commonly do not explicitly refer to any of these constraints, much less the ensemble we are assuming, but they are implicit in any observable that we use;

some projection from the system of interest. But why just from a physical system; why not also from other sources of information? Before turning to that, let me make a few more points here.

One is by way of a short list of more modern examples of ensemble variables. These are contained in thermodynamics, Debye-Hückel shielding (polarons) in ionized systems, normal modes (phonons) in solids, plasma modes (plasmons), Cooper pairs in superconductors, solitons in many systems, then on to the usual atoms, molecules, cells, ..., planets, stars, ..., humans, societies, etc. Some of these are often referred to as "collective variables", but they all are characterized by the above relationships.

Where do these ideas of ensemble, or collective, variables come from? How do we get to this reduction of information? After all, we (particularly in modern times) realize that there is a vast amount of dynamic information about which we are quite ignorant, and, generally speaking, the possibilities are truely limitless -*except*, we only consider very constrained situations! In other words, the reduction in information occurs only because we consider very limited spatiotemporal systems, which are defined by our interests. These involve:

* special circumstances* - *constrained environmental and historical conditions*

* special structures, dynamic/functional properties, which are consistent with all known laws concerning the behavior of the constituent observables*

These structures, dynamic/functional properties are only defined in some statistical (ensemble) sense - and the related ensemble variables are some average properties / structures / behaviors related to this ensemble. Generally, these ensembles and averages are not defined in detail (equilibrium statistical mechanics being one exception), but what ever they are, they cannot be inconsistent with known laws and with the system's environment/history.

In any case, these ensembles are never (repeat, never) deduced from any "first principles" - they are dictated by our observations (as to the "conditions" of the system), and then largely by our lack of knowledge - and by approximations, which in fact may violate basic laws in their details, but which can be rationalized in some limiting sense. Certainly one of the most important examples of this are the ensembles used in equilibrium statistical mechanics. The assumption (ignorance) contained in the Boltzmann-Gibbs distribution is that the state of the system depends only on the one constant of the motion that we generally know, the energy, E (sometimes the remaining eight known time-independent classic constants of the motion are introduced, when appropriate). There are, of course, something like 10^{23} other constants of the motion which we ignore, based on rationalizations, some of which have only become rationalizable in fairly recent time. Issues like this have been pointed out in Kinchin's wonderful little book [1], and our recent understanding of the sensitivity of the dynamics in virtually all systems, has added significant credibility to what we have assumed all along. The importance of this fact has yet to be widely recognized (e.g., Boltzmann's stosszahlansatz is, in fact, a stosszahlsatz). In other words, Mother Nature has been very considerate of our ignorance!

Also, as was nicely discussed by Garfinkel [2], and noted in my elementary textbook [3], the "derivation" of the Gibb's distribution, $\exp(E/kT)$, is based on an approximation that requires the violation of "a small amount" of energy conservation - which is becomes "insignificant" in the limit of infinite systems. It is not so much that an approximation had to be used, but it had to be one that violated a known law of physics. You can get much more of a break with deductive reasoning than that! It should also be pointed out that Garfinkel gave a very nice detailed example of ensemble reasoning in his analysis of how we treat predator- prey systems (we don't worry about which fox is behind what tree when some particular rabbit comes along, etc.). Such examples make it abundantly clear that our understanding of all systems is based on assumed (nondeductive) ensembles.

7.6 Implicit Order and Explicit Order (Understanding); Emergence

One of the most original and profound thinkers to explore issues related to the fundamental character of Nature, and our ability to scientifically understand, was the highly respected physicist, David Bohm, who died in 1992. In addition to his early foundational considerations, noted in the last section, he has produced a number of writings concerning his thoughts and discussions with others, delving into many basic issues [1]. Among these concepts, Bohm has introduced what he calls the Implicate Order [2], which recently he presented in a brief, and one of the more accessible discussions of what he envisioned [3]. An important area of his concern deals with quantum mechanics, and his examples are frequently referenced to this concern. Within this context, he discusses several examples of what he means by implicate order. One involves the storage of an image in a hologram, and the second involves the use of drops of colored liquid in a clear, highly viscous fluid between two cylinders. If the cylinders are rotated in opposite directions, the drops of fluid become sheared in structure, and ultimately become extended in a toroidal region around the axis of rotation. Both the hologram and this toroidal region have implicate order, in the sense that, while the information contained in them is not obvious, it can be recovered by suitable illuminations, and by reversing the rotations of the cylinders. The point of particular interest to Bohm is the spatially extended (nonlocal) nature of this Implicate Order - this concept he felt is fundamental to an understanding of the underlying character of Nature. Bohm was addressing a much more metaphysical question than I am focused on - indeed, this is a good example of shifting to a scaffolding metascience program, from metaphysical issues.

IMPLICIT AND EXPLICIT ORDERS

The insights of Bohm have stimulated me to reformulate some technical features of both mathematical models and computer outputs, which I had been attempting to characterize for some time, with little success. I have come to realize that this new description has broad applications, and implications, which gives new insights into the scientific approach of understanding natural phenomena (a metascience). More specifically, it reveals what underlies the process of obtaining information from all three sources of information used in Science; and the subsequent use of this information to obtain and understanding of dynamic phenomena.

This has led me to the concept of an "implicit order" (not to be confused with Bohm's deeper quest), which applies to each source of scientific information, namely natural phenomena (NP), mathematical models (MM), and computer explorations (CE). The details of what precisely is implicit will, of course, differ in each of these cases. It perhaps comes closest to what Bohm envisioned as it relates to natural phenomena, but even here it does not address the spatiotemporal aspects of reality, but emphasizes the implicit orders in nature, which we only explicate in limited domains. However, the implicit order of NP certainly touches upon fundamental metaphysical concepts, which I do not want to pursue here. To avoid these distinct metaphysical issues, I will first discuss the concept of implicit order as it arises in the other two (formal) sources of information. In these contexts the implicit order will be readily recognized as having been amply demonstrated by many very dramatic dynamic discoveries over the past century.

First I need to make clear what I mean by an "order". An "order" will signify the existence of a relationship between some set of observables (or potential observables in the future). As discussed previously, all scientific knowledge (understanding) rests upon the discovery of such relationships between a sets of observables; in the present terminology, scientific knowledge requires the discovery of some "order". It should be recalled that the terminology "observables" has been extended in its usage to all three sources of information, namely physical observables (PO), mathematical observables (MO), and computational observables (CO). Of course, of paramount importance for the physical sciences are the POs, but this concept of orders is very usefully extended to the formal sources of knowledge as well.

Now the concept of an implicit order can be made most simply and concretely by considering either mathematical equations or computer algorithms. Obviously such equations and programs are based upon a relationship between the variables being used. In a dynamic context, this is a relationship between the variables at "two-instants" or "two-steps" in time (and perhaps space). In a very real sense, such equations and programs have an "explicit order"; that is, one which we can easily recognize when we observe the equations (the symbols). Indeed, if we generate the equations or programs, we have this relationship in mind from the outset. So that's an explicit order of the equations. It may or may not turn out to be scientific knowledge (in a physical sense), depending on how, or whether, we can relate it to physical phenomena, but that's not the present issue.

The point here is to simply note that, contained within these equations is an infinite number of dynamic situations, none of which we know in any detail, until we distinguish some observables, either by some analysis of the MM, or by compressing the data output of some run of a CE (using some initial conditions). Obviously, we assume that we will subsequently be able to uncover some order (relationships between the observables), with a little thought and insight, otherwise we wouldn't bother with the whole business. So we have this faith that these equations contain some (initially) hidden order within them, in other words, an "implicit order". And our goal is to discover some "explicit orders" through the above processes. At first glance, this may all appear fairly obvious and uninteresting, but this new point of view opens a whole new perspective that is very revealing.

The principal new perspective that we acquire is that, even when we know quite explicitly the relationships that we have put into equations/algorithms, we have no assurance that we know much about the orders that are implicit in those equation/algorithms. Indeed, many examples over the past century, which deal with the dynamics of even relatively "humble-looking" system, have amply demonstrated that such equations can yield quite extraordinary, unexpected explicit orders.

The list begins at least with Poincaré's introduction around 1890 of a new method of analysis (outlined in section 4), which led to the uncovering of an unimaginable explicit order between solutions of the three-body problem (the "Poincaré tangle"); it includes a variety of unexpected solutions in general relativity (one explicit order caused Einstein to "mutilate" his equations [wei]); the mathematical discovery of the explicit order of "Bernoulli-sequence" randomness between the solutions of a simple forced oscillator equation; the establishment of another unimaginably complicated explicit order between solutions associated with equations that contain a certain type of "homoclinic solution"; the mathematical discovery of broad groups of nonlinear equations that contain the explicit order of self-sustaining localized spatiotemporal disturbances ("solitons"); this unexpected order is the genesis of the lack of presupposed irreversibility in some systems (a "small discovery", Fermi).

This and many other implicit orders have been uncovered with the help of computers. The list is long indeed, but to mention a few: the discovery by Kruskal and Zabusky of solitons, implicit in algorithms of simple PDEs; Lorenz's discovery of the implicit order of "chaos" and "strange attractors", characterized by the localized, yet exponential separation of nearby solutions, implicit in highly simplified models of fluid flows (see section 4); the quite extraordinary list of explicit orders that have been uncovered from the simple "logistic-map" dynamics, $x(n+1) = c * x(n) * (1 - x(n))$ $(n = 0, 1, 2, ...; \ \ 0 < x < 1, 0 < c < 4)$. It is by no means certain that all of the implicit orders of this equation have been discovered; one can go on to recount the many varieties of fractal, self-similar, "life-like", etc. explicit orders that have been discovered to be implicit in many simple algorithms.

IMPLICIT ORDER WITHIN	PROJECT OUT	EXPLICIT ORDER (RELATIONS)
MM	→	**MO (DEDUCED RESULTS)** **Poincaré, Levinson, Smale, Turing,** **Kolmogorov-Arnold-Moser,** **Gardner-Greene-Kruskal-Mirua** **Yorke, Oono, Shil'nikov**

We have learned here that :

1) "Humble" equations can contain unexpected, and dramatically important dynamic properties

2) There are a number of these dynamic properties that are common to many math models of physical systems - their implicit orders significantly overlap, yielding "universalities".

CE → **Fermi-Pasta-Ulam, Mandelbrot Kruskal-Zabusky, Lorenz, May, Feigenbaum, Metropolis-Stein-Stein, Ott-Grebogi-Yorke**

Many other forms of projections need to be developed from CE, particularly those that are more abstract, and exploratory in character. This includes Artificial Life, Artificial Intelligence, Economic Markets, Traffic Flows, Ecological, Military, etc. dynamics. The first order of business in many is to identify, from the wealth of output data, what are the important (communal) observables, and to establish their importance by finding relationships between some of them (obtaining knowledge/understanding). Then they will possibly become part of Science.

THE IMPLICIT ORDER IN NATURE (the source of the explicit orders, "governing laws of Nature")

This makes it much clearer to appreciate that the implicit order within Nature, which is the philosophical basis of all scientific research, is immensely more rich than the very limited projections that we are capable of even imagining, much less accomplishing. It is manifest that there is an infinite amount of information out there in the universe that will never be accessible to humankind, which will forever restrict our ability to find relationships within "sensitive phenomena" - including cognitive processes.

Along these lines, it is both amusing and discouraging to read Weinberg's recent "scientific analysis" for rejecting astrology [4]:

"... astrology sometimes point to the undoubted effects the effects of the moon and sun in producing tides, but the effects of the gravitational fields of the other planets are much too small to have detectable effects on the earth's oceans, much less on anything as small as a person."

This, of course, completely confuses the issue of size and sensitivity. The brain is undoubted a highly sensitive dynamic system, neurotransmitters (among many other things) being what they are. The functional implications of this sensitivity is presently wholly unknown, but its susceptibility to extra-sensory influences from the environment is quite certain. Certainly, if some experimental observations can be influenced by a passing truck in the street, one cannot dismiss what the brain may environmentally react to in some functional manner. We are, quite assuredly, all dynamically connected to our environment to one degree or another - and it is simply arrogant to dismiss the possible importance of such connections. Conversely, the burden of proof that such functionally important connections exist, remains a challenge for the future.

This leave mute the issue of whether any such laws will ever be uncovered in the future. It is important to emphasize that, while the existence of some general order in Nature is a fundamental tenant of Science, there is no method that one could ever establish that would prove that some particular set of laws constitute "The Governing Laws of Nature" - we can never check any such set of laws against all possible observations, thereby verifying their generality.

Metascience is not concerned with these issues, which have no scaffolding content, but focuses on generalizing what has always been our means for understanding natural phenomena. This will be explored further in what follows.

[1] D. Bohm, "Unfolding Meaning: a weekend of dialogue with David Bohm" (Ark Paperbacks, London, 1987) —, "Thought as a System" (Routledge, London, 1992)

[2] D. Bohm, "Wholeness and the Implicate Order" (Ark Paperbacks, London, 1983) D. Bohm and F. David Peat, "Science, Order, and Creativity" (Bantam Books, Toronto, 1987)

[3] D. Bohm and B. J. Hiley, "The Undivided Universe" (Routledge, London, 1993)

[4] S.Weinberg, p. 49 in "Dreams of a Final Theory" (Pantheon Books, N.Y., 1993)

7.7 Bi-Level Hierarchical Reduction/Synthesis (Emergent Knowledge)

** Discover a physical phenomenon - meaning a reproducible (at some level) relationship between a set of observables

The discovery of some natural phenomenon, and the conditions under which it occurs, by observations and/or experiments. Raise the questions, "Why does this phenomenon occur under certain constrained conditions?. Which of these environmental/structural/etc constraints are essential?"

** Determine the physical conditions under which it is found to occur; these are the "constraints" associated with the phenomena they may be structural, temporal, functional, dynamic, energetic, etc. The constraints are characterized by some macroscopic conditions concerning the system.

** Obtain a dynamic model for this constrained physical system, which involves variables that can be related to the constraining conditions; that is, some limitations on the dynamics/conditions of these variables, implied by the constraints, can be explicitly expressed. Most frequently these limitations will be associated with some ensemble (statistical) characterization of limitations on the variables' possible states. (e.g., populations, concentrations, densities, temperature, ages,...)

** Discover how these constraints produce, in a statistical sense, an approximate correlation between some set of dynamic variables of these equations; this correlated set of variables can be characterized as 'collective variables', or 'correlates', or 'ensemble variables'. the latter best emphasizes the statistical association, but the middle characterization is shorter an more neutral than "collective variables", which is the expression commonly used in physics. So "correlates" will be used here.

Given these constraints, which can be characterized in some ensemble format, what are the correlated (collective, holistic, quasi-particle) variables of the system, whose interactions can deductively explain the occurrence of the observed phenomenon ?

** Determine the nature of the binary interactions between these correlates. Can we do better than this classic approach? Let's try!

Note that the possibility of interaction between correlates (as such) implies that they have a metastability that is sufficient to survive such interactions. This is one of the "micro-constraints" that must be satisfied, which should be automatically satisfied if (a) the macro-constraints are satisfied, and (b) these correlates have anything to do with the observed phenomenon.

** "Join" these binary interactions between all of these correlates in a manner that permits us to make a logical deduction of the observed physical phenomena.

** This deductive synthesis of correlates (ensemble variables) yields an understanding of this emergent phenomena

The importance of any mathematical model depends on the number of different natural phenomena that can be deduced from it (all satisfying some constraints). Even for the same constraints, there may be different correlates for different phenomena. Schrödinger's equation demonstrates these facts, but for severely limited phenomena.

More briefly, the bi-level hierarchical reduction/synthesis knowledge

One Level	$\rightarrow$	Observe Physical Phenomenon, and the necessary "macro-constraints"
One-Level-Down	$\rightarrow$	Obtain a Dynamic Representation of the System, such that the Macro-Constraints can be associated with constraints on the Dynamic "Micro-Variables". Discover how these constrained variables yield correlates, whose interactions can be shown to produce the observed phenomenon

The reduction/synthesis process can go in either direction:

"Macro-Observations"	$\rightarrow$	The interaction of correlates, statistically
	$\leftarrow$	defined by some "Micro-Variables"

Discover	$\longrightarrow$	Develop Theory
Empirical Conformation	$\longleftarrow$	Theoretical Prediction

What is to be noted is that the variables (correlates) responsible for the phenomenon at the upper level are less stable than the "Micro-Variables" (since the correlates require constraints on the micro-variables to exist). Generally this means that the correlates, and their associated phenomena, are more sensitive to environment, and hence have more adaptive/functional capabilities.

It is not at all clear how we should employ some "blending" of hierarchies. the above hierarchy is largely based on structural and stationary environmental coupling

[1] kinchin stat mechanics

[2] Garfinkel, A., "Reductionism" p. 443 in "The Philosophy of Science" (R. Boyd, P. Gasper, and J.D. Trout, Eds., MIT Press, 1991). Garfinkel's analysis is in direct contrast with the hierarchical, but microreduction views of P. Oppenheim and H. Putnam, "Unity of Science as a Working Hypothesis", p.405, Ibid. Garfinkel's article comes from Chapter 2 of his book, "Forms of Explanation" (Yale Univ. Press, New Haven, CT, 1981).

[3] E. A. Jackson, "Nonlinear Coupled Oscillators. I. Perturbation Theory, Ergodic Problem" (J. Math. Phys. 4, pgs. 551-558, 1963)

[4] D. Bohm, "Thought as a System" (Routledge, London, 1992)

[5] D. Bohm, "Wholeness and the Implicate Order" (Ark Paperbacks, London, 1983)

[6] D. Bohm and B. J. Hiley, "The Undivided Universe" (Routledge, London, 1993)

[7] S.Weinberg, p. 49 in "Dreams of a Final Theory" (Pantheon Books, N.Y., 1993)

7.8 Scientific Uncertainties:

As an example of a misguided view of what the future task of Science is about, let me quote from Stephen Hawking's "A Brief History of Time" (Bantam Books, 1988):

> "In effect, we have redefined the task of science to be the discovery of laws that will enable us to predict events up to the limits set by the uncertainty principle"

One point being made here is simply that the uncertainty principle is the least of our barriers to the understanding most of Nature's phenomena. The actual sources of scientific uncertainty are many, and generally more important than the quantum mechanical uncertainty principle. It is these uncertainties that science needs to address in the future. Some of these are:

SCIENTIFIC UNCERTAINTIES

Quantum Uncertainties	**(Subatomic Phenomena)**
Macro-Uncertainty	**(What is Observed Hides)**
Empirical Uncertainty	**(Obtainable Information is Very Limited)**
Comprehension	**(Only Very Limited Information can be Comprehended)**
Dynamic Sensitivity	**(Continual Loss of Information)**
Extrasensory Influences	**(The Unknown Influences of Extrasensory Couplings To Universe)**
Limited Laws of Nature	**(Highly Restricted Empirical Projections of Nature)**
Contents of Mathematical "Laws"	**(Their Implicit Order, Limited Logical Projections)**
Computational Outputs	**(Comprehensible Observables, Meaningful, Projections Filtering, Compressions)**

7.9 East-West Conjunctions in Science; Relationships

Scientists of the West are justly proud of their heritage of success in developing many understandings of Nature's wonders. Without the concept that Nature could be studied in separate categories, and that some physical systems could be examined in isolation from their environment to some degree, Western Science would never have advanced as it has. The holistic view of Nature in the Eastern philosophies and religions, and their general distrust of the application of rational reasoning to natural phenomena, all compounded to make a natural science impossible. The spread of Western Science around the world, gives rise to the general impression expressed by Weinberg [1].

> "Modern scientific methods and knowledge have rapidly diffused to non-Western countries like Japan and India and indeed are spreading throughout the world. We can look forward to the day when science can no longer be identified with the West but is seen as the shared possession of humankind."

It might seem implicit in this statement, intended or not, that not only has there historically been a diffusion of "scientific methods and knowledge" from the Western countries to the rest of the world, but that this will be the cause of the desired "shared possession of humankind." I think that it is very important to counter any such impression, by pointing out a number of ways that that some of the fundamental insights of the Eastern cultures have already entered in technical aspects of modern scientific knowledge (quite distinct from the various metaphysical associations with quantum mechanics [2]). This fact needs to be made quite explicit, clearly appreciated, and consciously developed in the future. It will greatly enrich and extend the future metascience.

THE RELATIONAL AWAKENING

It is quite amazing, once one becomes sensitive to the fact, to see how pervasive the infusion of relational concepts into the basic components of science have become in the past century. By relational I mean that events and systems are not viewed in isolation, as for example in simple causal considerations, but in their relationship to other events and systems. In point of fact, as noted many times above, all equations are forms of relationships, but in the case of dynamic equations, they do not necessarily reveal much about their own content (their implicit order), much less about natural phenomena. Put another way, the explicit short-time relationship may reveal very little about long-time relationships. Here the temporal hierarchy clearly arises.

In Nature:

The importance of relationships in Nature is of course central to much of the wisdom of Eastern religions and philosophy, but here my focus is on modern science.

Certainly the examples of Mendel, Darwin, and Weissman might come to mind first. Evolution is nothing if it is not about the impact of relationships that occur in Nature.

The culmination of this in recent times is the discovery of the genetic code, and some of the relationships that have been established between amino acid sequences and functional properties of humans, animals, and plants. Relationships are indeed of central importance in all of the more complex phenomena, be they in economics, psychology, biology, physics, chemistry, geology, astronomy, meteorology, etc., and these discoveries have been the hallmark of much of their modern development.

In fact, once one focuses on this notion, it is difficult to see why it wasn't more central to science all along. Why had causality and predictions been such a dominant view? Perhaps in part because of practical applications, but also because the phenomena of concern were often of sufficient simplicity that analytic solutions of approximate models could be readily obtained. Whatever the reason, these insights have certainly been joined, and often superceded, by the need to develop methods for describing and analyzing relational concepts.

There are many dynamic concepts which have no meaning except in a holistic context - where behaviors at one time are related to behaviors at quite different times, or relationships that must exist between a group of different physical states. For example:

- a stationary state
- periodic behavior
- attractors, and their basins of attraction transient phenomena
- intermittency
- metamorphosis

These, and others, take on geometric (topological) characterizations in space, or in phase-space representations. Some of these are:

- linked and knotted relationships [3]
- "fractal" characteristics of dynamic sets [4,5],
- "fractal" physical structures [6,7]

The holistic character of mathematical structures has been commented upon by Penrose [8], and of course there are important topological ("equivalence") relationships that have long been noted between different physical structures [9].

What follows are but a few of the relationship issues that arise in the two formal (logical) sources of scientific knowledge:

In Mathematics:

At the end of the last century, three different mathematical fields were introduce, each based on concepts of relationships.

a) Minkowskian (Non-Riemannian) geometry, which was so central to Einstein's development of general relativity - a physical theory which is all about relationships of matter in space-time.

b) Poincaré's development of topology, and its application to dynamics in phase space. In this space, the concept of topological equivalence, bifurcations, attractors, their basins, flows on "fast", "slow", stable, and unstable invariant manifolds, and numerous other basic ideas are all about various relationships between the dynamics of different physical systems.

c) Cantor's development of set theory, in which sets are defined in terms of common features of different "elements" - some common relationship. The beauty of Poincaré's idea of maps associated with the flows in phase space, made contact with Cantor's set theory and ultimately fractals, self-similarities, etc. These all give rise to holistic visions of Nature.

d) The recognition of the importance of the roles of invariant manifolds (i.e., k-dimensional regions of phase space, whose states are dynamically connected); these distinguish sets of states that are: stable or unstable to some other set; fast and slow processes (temporal hierarchy); related by some "topological equivalence"; variously "enslaved" to other sets; subject to "dynamic catastrophes" when the environment changes.

In Computations:

Here, in this newest branch of scientific knowledge, there is much to be learned about relational concepts. One of the areas of greatest need is to find ways of extracting comprehensible observables from the over-abundance of "data-facts", which are provided by computers. The first need is to discover the technical compressions of this data into meaningful (and communally acceptable) "observables." This is essential, in order to avoid what Holland calls "eye of the beholder" errors [10]. The next step is to discover relationships within some sets of these observables - again, knowledge is based on the discovery of such relationships.

There are many examples of the need to make such discoveries in computational models of dynamic systems. To name a few, there are complex models in economic, ecological, traffic, geopolicitcal, various networks (neurological, metabolic, chemical,...).

One interesting area is to try to understand how some algorithmic methods may accomplish dynamic functional tasks. One approach [11], evolutionary computations, employs genetic-algorithm searchs of dynamic rules in cellular automata systems, seeking those that can accomplish some global recognitions with only their local rules. By studying the evolution of some solution, insight is gained into the importance of relationships between the dynamics in different portions of the system.

[1] S. Weinberg, Dreams of a Final Theory, p. 190

[2] e.g., F.Capra, The Tao of Physics (Bantam Books, Toronto, 1984)

[3] A.T. Winfree, Persistent tangled vortex rings in generic excitable media, Nature 371, 233-236 (1994)

[4] Ott, Grebogi, and Yorke – reference

[5]J. Briggs, Fractals, the patterns of Chaos (Touchstone, N.Y., 1992)

[6]D.L. Turcotte, Fractals and chaos in geology and geophysics (Camnbridge Univ. Press, 1993)

[7] E. Porter and J. Gleick, Nature's Chaos (Viking, N.Y., 1990)

[8]R. Penrose, Must mathematical physics be reductionist? p. 12-26 in Nature's Imagnination (J. Cornwell, Ed., Oxford Univ. Press, 1995)

[9] D'Arcy W. Thompson, On Growth and Form ; the complete revised edition (Cambridge Univ. Press, 1942; Dover Pub., 1992)

[10] J. Holland, p. 171 in Hidden Order (Addison-Wesley, 1995)

[11] J.P. Crutchfield, "Discovering Coherent structures in Nonlinear Spatial Systems" Santa Fe Institute Working Paper, 91-09-034 (1991)

J. P. Crutchfield and M. Mitchell, "The Evolution of Emergent Computations" Santa Fe Institute Working Paper 94-03-012 (1993)

R. Das, J. P. Crutchfield, M. Mitchell, and J. E. Hanson, "Evolving Globally Synchronized Cellular Automata", Sixth Int. Conf. Genetic Algorithms (1995)

7.10 Some Complimentary Dualities in Science ("Yin-Yangs")

What follows is a random assortment of ideas about concepts that are inter-related, complimentary, variously joined, and co-existing. The selection is biased by the discoveries that have been made over the past century within the area of dynamic phenomena. At the right there are vague indications of what I'm driving at, all of which would benefit from elaborations and other insights.

Chaos/Order	**(Known Examples: "Out of", "Within", and "Co-existing")**
Determinism/Randomism	**(Temporal and Quantitative Degrees; Dimensions; Implicit Aspects)**
Reductionism/Holismism	**(For some enjoyable insights into**

	this important dualism, see [1])
Reduction/Synthesis	**(Co-joined Actions, Bi-level Hierarchies)**
Hierarchies/Networks	**(Various Hierarchies Somehow Networked)**
Attraction/Repulsion	**(Sets of States; Individual States)**
Approach/Diverge	**(Dynamic Relationships Between States of a System; Co-exist in Bounded Situations)**
Implicit/Explicit	**(Character of Relationships, Orders)**
Open/Closed	**(Systems, to Matter, Energy, Information Environmental Connections)**
Passive/Adaptive	**(Dynamic Processes; Responsive Relationship to Environmental Conditions)**
Conservative/Dissipative	**(Co-joined Concepts: The latter being a physical subset of the former)**
Randomize/Organize	**(Dynamic Relationships Between Parts; In bounded situations they can be kindred)**
Animate/Inanimate	**(The Role of Dynamic Feedbacks?)**
Local/Global	**(Views in Phase Space, Spatial, Temporal,...)**
Quantitative/Qualitative	**(Topology, Set Theory, Non-Riemannian Geometry,..)**
Static/Dynamic	**(Coexisting Attractors of a System)**
Homogeneity/Structure	**(Joining, Structuring Dynamics)**
Bifurcation/Stablity	**(In Changing Environment)**
Sensory/Extrasensory	**(What are the relationships?)**
Sensitive/Insensitive	**(Dynamic Phenomena, Universal Coupling)**
Life/Death	**(Explicit/Implicit Order Cycle? Metaphysics!!)**

[1] D. R. Hofstadter, Gödel, Escher, Bach: An eternal golden braid (Vintage Books, Random House, N.Y., 1979), Chapter X, "Ant Fugue"