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EXPERIMENTAL METAPHYSICS

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THE METAPHYSICS OF SCIENCE AT THE END OF A HEROIC AGE*

Actualities seem to float in a wider sea of possibilities from out of which they were chosen; and *somewhere*, indeterminism says, such possibilities exist, and form part of the truth. (William James)

1. INTRODUCTION

Roughly a hundred years ago, Charles Saunders Peirce and William James were seeking to articulate a philosophy consonant with the implications of Darwinian evolution that would translate into a set of guidelines for the conduct of the good life. As David Hollinger has noted, their philosophy was shaped by their assessment of "the integrity and durability of *inquiry*, on the one hand, and the tentativeness, fallibility and incompleteness of *knowledge* on the other": "for both Peirce and James scientific knowledge, as embodied in scientific laws, was tentative and approximate, it was the 'method' of scientific inquiry that was to provide a foundation secure and sturdy enough to support a modern culture'' (Hollinger, 1995: 20). And for Peirce the scientific community became the model for a democratic society: the problem of scaling from the small to the large posed no problem for him. In this he manifested the proclivity that Tocqueville had noted in the literature of the United States: ''the tendency in a society without traditions or barriers, to go at one leap from the individual to the universal'' (Matthiessen, 1947: 14).

In many ways, we are presently engaged in an exploration that parallels that of Peirce and James. But whereas their inquiry came at the end of a century that allowed them to believe in progress and convergence towards Truth, ours come at the end of a century that witnessed two of the bloodiest and most brutal wars in history, that recorded genocides on an unprecedented scale and that beheld the establishment and downfall of two ruthless totalitarian states whose emblems were Dachau and the Gulag. But the century also secured knowledge whose scope and stability is unparalleled. My presentation tries to assess the character of this new knowledge and its implications for an attempt at formulating a neo-pragmatic philosophy.

Feynman declared the century a ''heroic, unique and a wonderful age of excitement'' in fundamental physics.[1] Its basic tenets were global reduction and unification. The latter characterizes the hope of giving a unified description for all physical phenomena, the former the aspiration to reduce the numbers of independent concepts necessary to formulate the fundamental laws.[2] The

* *For Abner: With admiration and affection*

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impressive success of the enterprise since the beginning of the century has deeply affected the evolution of all the physical sciences, as well as that of the life sciences.

If the special and general theory of relativity and quantum mechanics are the theoretical high points of the first half of the century, the Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity and the establishment of the standard model of particle physics are the great achievements of "fundamental physics" during the second half. When Bardeen, Cooper and Schrieffer explained superconductivity in 1957, the validity of their model "finalized" nonrelativistic quantum mechanics.[3] The further study of the BCS model revealed the importance of "broken symmetries", a concept which was to play a central role in the further advances of particle physics.

The "standard model" that describes the strong and electroweak interactions in terms of quarks, gluons and three "generations" of leptons (and possibly a Higgs particle) is one of the great achievements of the human intellect. Its empirical confirmation during the 1980s marked the attainment of another stage in the attempt to give a unified description of the forces of nature. But ironically, the very concepts that helped achieve the important advances that led to the standard model have eroded the foundational tenets upon which the program is based. The ideas and concepts of symmetry breaking, renormalization group and decoupling that stemmed from a deeper study of relativistic field theoretical models adumbrate and justify a picture of the physical world that is *hierarchically* layered into quasi-autonomous domains, with the ontology and dynamics of each layer essentially quasi-stable and virtually immune to whatever happens in other layers. Physical theories that were thought to be fundamental have assumed a much more phenomenological character, and conversely theories that were thought to be phenomenological have assumed a much more foundational character (Georgi, 1989).

The second half of our century has also seen the waning of the Newtonian-Laplacian paradigm even in the macroscopic world, the domain in which it was thought to be applicable. The Laplacian demiurge viewed the world as a vast automaton, governed by deterministic and time-reversible laws, in which human beings appeared outside nature, endowed with free will and able to dominate, manipulate and exploit their environment. In this mechanical universe, rationality was identified with timelessness and equilibrium. Starting in the 1960s, new insights into chaos undermined the conventionally accepted tenets of predictability and control of classical physics once the impossibility of specifying with absolute precision the initial state of a system is taken into account. It became clear that within the framework of a deterministic Newtonian description, nonlinear systems with three or more degrees of freedom could develop chaotic – i.e. undeterminable and unpredictable – motion. A butterfly flapping its wing in Brazil can set off a tornado in Texas (Lorenz, 1967).

In both the biological and the physical sciences chance and contingency have become much more central in understanding the order in the world around us, and have become a more pronounced facet of our conceptualization of the origin of the

observed regularities and of our descriptions of them. Chance and contingency (in relation to order), hierarchical layering,[4] emergence (of order) and "systems" thinking may be said to be the characteristic concerns in the new metaphysics of science.[5] Thus Steve Gould and Niles Eldredge's theory of punctuated equilibrium, like Darwin's mechanism of evolutionary change, "is a claim about relative frequencies, not exclusivity" (Gould and Eldredge, 1993; 225). It is also a hierarchical extension of the theory of natural selection to levels both below individuals (gene and cell lines) and above organisms (demes, species, clades). And to buttress the theory Gould and Eldredge have grappled with the problem of how to give an operational definition of selection at the non-organismical level: whether in terms of emergent traits or in terms of emergent fitness (Gould, 1994). Analyzing the "laws of biology" Richard Lewontin (1990, 1996), Edward O. Wilson (1989), John Beatty (1995) and others have come to the conclusion that all biological generalizations about the living world are contingent outcomes of evolution. There are no invariable biological laws of nature. In Gould's memorable metaphor, were the tape of life replayed many times, it would have a different outcome each time (Beatty, 1995; Gould, 1989: 45–52, 277–291).

In cosmology, conjectures about the early universe have become a respectable field of inquiry by virtue of the discovery of the 3°K relic radiation and the great instrumental advances in observational astronomy,[6] – and they have suggested that the "laws of nature" have a history – an idea familiar to biologists and astrophysicists but novel to most physicists and chemists (Balashov, 1992; Schweber, 1993). Considerations of multiple universes have become commonplace (see e.g. Linde, 1990, 1994) and the more daring cosmologists have proposed something akin to a natural selection of physical laws, with different physical laws holding in different physical universes (Smolin, 1994). The former view that the physical laws of nature of widest scope are invariable and immutable has been replaced by one that endows them with an initial historical component, and even more daring proposals, that echo the notions advanced by Peirce that laws of nature mutate,[7] are being discussed in respectable scientific fora. But the obverse side of these conjectures should be stressed. We now know that the present laws of nature – such as quantum chromodynamics (QCD), quantum electrodynamics (QED) – have not changed since an epsilon of the big bang and that they are valid almost everywhere in our universe (except perhaps at its outer boundaries)[8] (Dyson, 1978).

It is stating the obvious to say that the computer has played a fundamental role in this transformation. But there is an aspect of the computer revolution that merits particular emphasis. The use of computers has focused attention on what is and what is not computable – in finite time – on universal computers of the Turing type.[9] Thus, the study of spin glasses and other disordered systems in condensed matter physics has shown that certain fundamental properties of such systems – e.g. the true ground state – are not computable in finite time (when the number of spins becomes very large).[10] These results, at the practical level, together with deep results about algorithmic computability in general, have challenged previously held notions about what is calculable "in principle". Thus it may prove impossible –

without some empirical input – to compute the binding energy of the deuteron or the excited states of the C^{12} nucleus starting from QCD, or to compute the ^5S excited state of the carbon atom starting from the standard model. I point to these two properties of carbon, because all heavy nuclei are built up in triple alpha-particle collisions in stars – the Hoyle–Salpeter process – by virtue of the existence of a 7.82 MeV excited state in the C^{12} nucleus. Similarly, the particular location of the ^5S excited state of the carbon atom is crucial in the formation of the tetravalent bond of C and is thus evidently a precondition for the possibility of life on this planet.

In an article in *Nature* in 1993 in which they reviewed the status of their theory of punctuated equilibrium, Steve Gould and Neil Eldredge commented on the fact that contemporary science has extensively replaced previously held convictions about computable, gradual, progressive, predictable determinism with notions of indeterminacy, historical contingency, chaos and punctuation, and has advanced an image of nature that emphasizes non-equilibrium conditions, and focuses on the multiple, the temporal and the complex. They noted that these transitions have occurred in "field after field" and cautioned that seen in this light punctuated equilibrium might only be "paleontology's contribution to a *Zeitgeist*" and warned that "that *Zeitgeists* as (literally) transient ghosts of time, should never be trusted". They concluded their article by declaring:

> Thus, in developing punctuated equilibrium, we have either been toadies and panderers to fashion, and therefore destined to history's ashheap, or we have had a spark of insight about nature's constitution. Only the punctuational and unpredictable future will tell (Gould and Eldredge, 1993: 227).

Though an unpredictable future may prove me wrong, I believe we have had "a spark of insight about nature's constitution" during the twentieth century. I believe that the shift is more than a swing of the pendulum rectifying the prevalent reductionist viewpoint that held sway throughout most of the century and that we have witnessed the abandonment of the Cartesian vision that: "philosophy as a whole is like a tree whose roots are metaphysics, whose trunk is physics, and whose branches, which issue from this trunk, are all the other sciences",[11] and have adopted a more Pascalian attitude that accepts contingency and probability as part of the order of things.[12]

My paper is structured as follows: in section 2, I discuss the traditional understanding of the regularities of nature in the physical sciences by outlining the history of how they were arrived at. In section 3, I consider briefly complexity in physics. In section 4, I outline some of the changes that have been brought about by the advances in elementary particle physics and cosmology. In section 5, I tentatively explore some of the implications of the new understanding.

2. REGULARITIES AND LAWS OF NATURE

The search for "the" ultimate constituents of matter has had a cyclic history. Since the beginning of the nineteenth century, when the search became empirically grounded, each stage was initially characterized by incoherence. This initial confusion gave way to a measure of clarity through classification and with the help of the latter replaced by some measure of order. Once that order was ascertained a new level of substance and structure was discovered, whose characteristics were elucidated, usually with the help of new instruments and technologies. Again, incoherence and confusion reigned until the regularities operating at that level were discerned, classified and modelled. Four such cycles are readily identified: the unraveling of the level of the chemical elements, that of the nuclei of atoms, then that of the constituents of nuclei and their associated entities (i.e. the hadrons, the strongly interacting particles like the neutron, the proton, and the various mesons) and most recently that of leptons,[13] quarks and gluons.

The case of the chemical elements is illustrative of the process. With Dimitri Mendeleev's periodic table, some measure of clarity was brought into the classification of the chemical elements. Moreover, by virtue of the gaps that existed in the classificatory scheme, Mendeleev in the 1860s predicted that further elements should exist with chemical properties that he could specify – and these were later discovered. However, the interpretation of the patterning and the elucidation of the meaning of the classificatory scheme had to await the discovery of the electron and the modelling of the nuclear atom. A phenomenological explication of the table, in terms of the quantized orbits that electrons could occupy in their motions around the positively charged core nucleus, was attempted by Walther Kossel in 1916. Expanding on these insights, Niels Bohr in 1920 gave a phenomenological explanation of the Mendeleev table, including the placement of the rare earths in it, based on his *Aubauprinzip*, according to which an atom could be considered to be built up by the successive addition and binding of electrons into orbits described by the old quantum theory. A more "fundamental", dynamical explanation had to await the invention of quantum mechanics and the formulation within that framework of the Pauli exclusion principle.[14]

Until the discovery of natural radioactivity at the end of the nineteenth century, most chemists and physicists thought that the periodic table was a permanent, invariable regularity of nature, reflecting the immutability of the chemical elements. Thus, in his inaugural lecture as the first Cavendish Professor in 1867, Maxwell remarked that:

> the molecule ... is a very different body from any of those with which experience has hitherto made us acquainted. In the first place its mass, and the other constants which define its properties, are absolutely invariable; the individual molecule can neither grow nor decay, but remains unchanged amid all the changes of body of which it may form a constituent.
>
> In the second place it is not the only molecule of its kind, for there are innumerable other molecules, whose constants are not approximately, but absolutely identical with those of the first molecule, and this whether they are found on earth, in the sun, or in the fixed stars.

But not everyone was of that opinion. After the appearance of Herbert Spencer's and Charles Darwin's writings, evolutionary concerns came to occupy a more central and accepted position in scientific activities. Thus, even though the idea of the evolution of stellar systems and that of our own planetary system were familiar to astronomers at the beginning of the nineteenth century by virtue of the nebular hypotheses that Immanuel Kant, William Herschel and Pierre Simon de Laplace had advanced,[15] these problems attracted attention once again only after Herbert Spencer and Charles Darwin had advanced their evolutionary models. In 1908, George Ellery Hale commented:[16]

> It is not too much to say that the attitude of scientific investigators towards research has undergone a radical change since the publication of the *Origin of Species*. This is true not only of biological research, but to some degree in the domain of the physical sciences. Investigators who were formerly content to study isolated phenomena, with little regard to their larger relationships, have been led to take a wider view (Hale, 1908: 1).

Under the influence of Darwinian ideas, Norman Lockyer (1873, 1887, 1900), and William Crookes (1879, 1886, 1887, 1889, 1898) proposed theories of the evolution of the elements: chemical elements were composite structures that had developed through an inorganic process of Darwinian evolution.[17] In the United States, these notions were popularized by Lester Ward (1889, 1913).[18] Although widely discussed, Lockyer's and Crookes's proposals were recognized as speculative. The discovery of natural radioactivity by Becquerel in 1896 put an empirical stamp on the discussion. By the beginning of the twentieth century, the elucidation of the phenomenon by Rutherford, Soddy, Pierre and Marie Curie and others made it clear that the entry for the atomic weights of some of the elements in the Mendeleev table – e.g. thorium and uranium – would be slightly different a thousand years hence, the atomic weight of an element being a reflection of the terrestrial relative abundance of its various isotopes. But since the lifetimes of most isotopes are short compared to the age of the earth (except for the alpha-decays of elements heavier than lead), the table does display an "ahistoric" character to a high degree of accuracy.

Answers to the question about the "origin" of the various isotopes found on earth had to await the maturation of nuclear physics and astrophysics during the 1920s and 1930s. With the advent of the Bohr theory of atomic constitution, advances in astrophysics[19] made it clear that the chemical regularities embodied in the periodic table reflect the ambient conditions on earth: there are no *chemical* laws in stellar interiors (where atoms are fully ionized). What is not made explicit in the statement of the periodic table is the context in which the regularity applies, and how these conditions came to be.

Quantum mechanics could give explicit answers to these questions regarding origins. The formulation of non-relativistic quantum mechanics was a revolutionary achievement. Its underlying metaphysics is atomistic. Its success derives from the *confluence* of a theoretical understanding, the representation of the dynamics of microscopic particles by quantum mechanics, *and* the apperception of a quasi-stable ontology, namely electrons and nuclei, the building-blocks of the entities – atoms, molecules, simple solids – that populated the domain that was being carved out. Quasi-stable means that under normal terrestrial conditions, electrons and (non-radioactive) nuclei can be treated as *ahistoric* objects, whose

physical characteristics are seemingly independent of their mode of production and whose lifetimes can be considered as essentially infinite. Quantum mechanics indicates that structured systems can only have discrete states, and enables one to calculate the characteristic energies involved.[20] If the ambient temperature, T, of the surrounding is such that kT is much larger than the binding energies of the compound structures under consideration, they will dissociate, and the physical processes involved must be described in terms of their constituents. If, as on the surface of the earth, the energy available is that characteristic of chemical processes, an atom can be considered a simple object – composed of a nucleus and a surrounding cloud of electrons – that exhibits both stability and plasticity. This stability and plasticity of atoms allows them to further combine with one another and to form more composite objects, such as molecules and solids. And the possible composite structures that can be created from the "elementary" constituents are almost limitless.

The quantum mechanical explanation of chemical bonding resulted in *the unification of physics and chemistry*. In 1929, in the wake of the enormous success of nonrelativistic quantum mechanics in explaining atomic and molecular structure and interactions, Dirac, one of the main contributors to these developments, in a now famous quotation, declared that, "The general theory of quantum mechanics is now almost complete". Whatever imperfections still remained were connected with the synthesis of the theory with the special theory of relativity. But these were

> of no importance in the consideration of atomic and molecular structure and ordinary chemical reactions ... The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the exact application of these laws lead to equations much too complicated to be soluble (Dirac, 1929).

Dirac's assertion is still valid, but as emphasized by Anderson:[21]

> 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 the 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. The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity (Anderson, 1972).

Still, I will follow Gell-Mann and other particle physicists and look upon physics as more foundational (not fundamental)[22] than chemistry, because:

1. The laws of physics encompass in principle the phenomena and the laws of chemistry.
2. The laws of physics are more general than those of chemistry.

That is, those of chemistry are valid under more special conditions than those of physics (Gell-Mann, 1994).

A comparable story unfolded in nuclear physics – though the story is more involved. Again, it required the apperception of a quasi-stable ontology – in this case, neutrons and protons – whose mass, electric charge and magnetic moment were empirically determined. One further feature rendered the application of quantum mechanics in the nuclear domain more explicitly phenomenological than was apparent in the atomic case. The forces between the nucleons were initially unknown (in contradistinction to the Coulomb and the magnetic interaction between charges). These forces had to be ascertained through scattering experiments, and then used to see whether they could account for the observed regularities in nuclear structure.[23] With the recognition that for low energy,[24] neutrons and protons can be considered the "elementary" constituents of nuclei, and with the advent of Fermi's field theoretic explanation of beta decay, the quantum mechanical description of nuclear structure and of nuclear reactions allowed quantitative calculations to be made of the energy productions in nuclear reactions in stellar interiors. Its empirical success resulted in the *unification with nuclear physics* of the branches of astrophysics dealing with stellar constitution and energy production in stars, and the formation of the subdiscipline of nuclear astrophysics.

Similarly, once the world of hadron physics had been classified and elucidated and the standard model established, a unification of "elementary particle physics" and cosmology ensued (see e.g. Turner and Schramm, 1979; Schramm, 1983; Linde, 1985). I shall return in section 3 to an examination of both the meaning and the limitations of the implied unification of physics and chemistry, nuclear physics and astrophysics, and "elementary particle physics" and cosmology.

It is uncontestable that these unifications speak of the *robustness* of quantum mechanics and it is worthwhile to try to identify the attributes that are responsible for it. To do so, it is important to differentiate between the mathematical *structure* employed – Hilbert spaces (the elements of which are identified with the possible state of systems), self-adjoint operators (associated with the observables of the system), the implementation of the time evolution of state vectors by a unitary transformation – and the *specific equations* associated with particular systems (e.g. the Hamiltonian used to give a nonrelativistic description of a helium atom or the field theoretic Hamiltonian describing the interaction between-positrons and the (quantized) electromagnetic field).[25] Evidently, the *mathematical structure* can be expressed in a language that is general enough to be able to represent important features of nature over an amazing range of energies. On the other hand, the specific theories and their associated equations have a much narrower domain of validity – usually determined by the masses of the particles encompassed by the theory.

This same disjunction appears in the various models developed within the framework of quantum field theory (QFT) to describe the subatomic world. QFT, the synthesis of quantum mechanics and special relativity, is likewise atomistic in nature. The particles described by the fields that appear in the Lagrangians are conceived as the elementary constituents of the domain to be described by that field theory.

QFT was developed during the late 1920s as a general framework to describe quantum mechanically the interaction of charged particles with the electromagnetic field. During the 1930s, the formalism was extended by Enrico Fermi to model β-decay phenomena and by Hideki Yukawa to explain nuclear forces. All these field theories have the following features in common: they synthesize quantum mechanics and special relativity and they are "local", meaning that the interaction between the fields is represented as taking place at a single point in space-time. But local quantum field theories are flawed: their perturbative solutions are divergent, the infinities that are encountered being a consequence of the locality of the interaction.

After the Second World War, stimulated by reliable and precise measurements of the level structure of hydrogen by Willis Lamb and by Isidor Rabi, renormalization theory was formulated to circumvent the divergence difficulties encountered in higher-order calculations in quantum electrodynamics (QED). Freeman Dyson was able to show that a "renormalization" of the charge and mass parameters (and a rescaling of the field operators) that enter in the Lagrangian describing the theory were sufficient to absorb all the divergences in QED. More generally, Dyson demonstrated that only for certain kinds of quantum field theories is it possible to absorb all the infinities by a redefinition of a finite number of parameters. He called such theories renormalizable. Renormalizability thereafter became a criterion for theory selection, and played an important role at arriving at the standard model of the electroweak and strong interactions.

During the past twenty years, our understanding of quantum field theories and of renormalization has changed dramatically. What has emerged from the work of Kenneth Wilson[26] and Steven Weinberg is a more limited view: all extant theoretical representations of phenomena are only partial descriptions that depend on the energy at which the interactions are being analyzed. Successful quantum field theories are low energy approximations to a more fundamental theory that may or may not be a field theory. What Weinberg and others have shown is that the reason that quantum field theory describes physics at accessible energies "is that any relativistic quantum theory will at sufficiently low energies look like a quantum field theory" (Weinberg, 1995).

It may be that the empirically verified relativistic quantum theories are the low energy approximation of a superstring theory that describes the "fundamental" entities as extended, nonlocal, objects (that still interact locally), encompasses quantum gravity, explains the observed four dimensionality of space-time, accounts for the observed dimensional constants in QCD and electroweak theory, and gives new insights into the structure of QM.[27] The point I wish to emphasize is that these reconceptualizations have led theorists to structure the microscopic and sub-microscopic world hierarchically, and that the justification for this viewpoint does not depend on a "final" theory, should such an ultimate theory exist and be realizable. One, thus, operates fairly securely within a framework whose *ultimate foundation is unknown*.

For relativistic quantum field theories the crucial step in the formulation of this hierarchical picture was taken by Symanzik and by Appelquist and Carrazzone.

They proved that in renormalizable QFTs to all orders of perturbation theory if some fields have masses much larger than the others, a renormalization prescription can be found such that the heavy particles decouple from the low energy physics, except for producing renormalization effects and corrections that are suppressed by a power of the relevant experimental energy divided by a heavy mass. Their proof has become known as the decoupling theorem. An important corollary to this theorem is that the low energy physics is describable by an effective field theory, which incorporates only those particles that are actually important at the energy being studied. A description of physics by an effective theory is context-dependent, the context dependence being delimited by the experimental energy available and is embodied in the cut-offs that are represented by the heavy particles. The hierarchical picture of the physical world implied by effective field theories explains why the description at any one level is so stable and is not perturbed by whatever happens at higher energies, and thus justifies the use of such description. In this hierarchical depiction each level is populated by its own ontology, yet the picture recognizes connections between levels through what are known as the renormalization group equations. It, thus, allows the possibility for the emergence of complexity and novelty without rejecting the possible description of the mechanism of emergence in terms of component parts.

In condensed matter physics renormalization group methods were initially used to show that the detailed physics of matter at microscopic length scales and high energy is *irrelevant* for critical phenomena. What is important is the symmetry involved, the conservation laws that hold, the dimensionality of space and the approximate locality and additivity of the interactions. The method is not restricted to critical phenomena. It has been extended to show that for a many-body system, integrating out the short wavelength, high frequency modes (which are associated with the atomic and molecular constitution), one can arrive at a hydrodynamical description that is valid for a large class of fluids, and which is insensitive to the details of the atomic composition of the fluid. The particulars of the short wave (atomic) physics are amalgamated into the parameters – density and viscosity – that appear in the hydrodynamic description. The physics at atomic lengths – and *a fortiori* high energy physics – has become decoupled.

It should, however, be noted that the different levels are not completely separated – there is no sharp demarcation between an atomic beam and the air coming out of a vent. There are new phenomena that emerge as one goes from atoms to fluids – and, in many circumstances, it is useful and efficient to describe them in terms of extremely accurate, autonomous "phenomenological" macroscopic laws such as the Navier–Stokes equations. What needs to be explained is their "universality", and why a macroscopic description involving only density and viscosity is possible for a very large class of fluids. The parameters, such as density and viscosity of the fluid, that enter in the Navier–Stokes equations, the classical description of hydrodynamical phenomena, encapsulate the irrelevance of the short distance behavior. The central fact in a hydrodynamic description is that one is describing a macroscopic system containing an immense number of atoms, each of which is undergoing a very large number of scatterings in a macroscopic instant dt. A hydrodynamic description, thus, entails summing over a large number of elementary events which brings in the law of large numbers. The use of the law of large numbers is crucial in obtaining deterministic autonomous macroscopic equations like the Navier–Stokes equation or Fourier's law of heat conduction. Lebowitz has repeatedly emphasized that the law of large numbers is crucial not only for ensemble averages, but also for the almost sure values of quantities that fluctuate at the microscopic scale. It is the latter fact that guarantees that the macroscopic equations describe the actual evolution of single configurations of the physical system (Lebowitz, 1988).

High energy physics and condensed matter physics have become essentially decoupled in the sense that the existence of quarks, or that of any new heavy mass particle discovered at CERN or elsewhere, is irrelevant to the concerns of condensed matter physicists – no matter how great their intellectual interest in them may be. This fragmentation has resulted in the exploration and conceptualization of the novelty capable of expression in the aggregation of entities in each level – novelty that is evidently contained in the "foundational laws"[28] at that level and that does not challenge their "foundational" character. The challenge is how to conceptualize this novelty – that is what Anderson meant by the statement "More is different". It is the quasi-independence of the levels and the possibility of describing each in terms of its own ontology and dynamics, dynamics that can be considered "foundational" when addressing that level, that give this viewpoint its attribution of being post-modern.

3. THE STUDY OF COMPLEXITY

Until fairly recently, most physicists thought of themselves to be looking for those laws of nature that have the widest scope in space and time, and they called these "fundamental". They saw themselves as secular priests who sought basic principles and concepts, and who translated them into mathematical formulations in terms of which they hoped all further understanding could be based. This collective vision cemented the community together, particularly after the Second World War. Until the 1970s, physicists were inclined to implement this vision by studying simple systems, or when the systems considered were more complicated, they were chosen to be ordered systems. Disorder was characterized as the absence of order and was perceived a negative feature. This was true not only of theoretical solid state physicists, with their calculations of the band structure of materials with crystalline structure, but also of experimentalists where new techniques of zone refining had produced materials of astounding purity. The huge success in being able to state simple laws, formulated in terms of simple equations,[29] led to the illusion that simplicity in formulation should lead to simplicity in outcome. The illusion was reinforced by the very selection of problems and systems, which were picked precisely because they had simple, predictable outcomes. The systems studied usually also had the property that they maintained their "degree of complexity" during their temporal evolution. Thus, the many-body systems studied in superconductivity and in critical phenomena – the two areas of condensed, matter physics that can claim the greatest success and advances in understanding of the properties of matter – have reversible histories and relatively simple, predictable outcomes.

The world, however, does not conform to this pattern. It has a history that shapes its further evolution and tends not be predictable. The world – even the physical world – "is wondrously complicated and bewilderingly diverse". How does complexity arise from the simplicity that governs the component parts? "How can organization develop from blind law and naked chance?" (Kadanoff, 1993: 385).

Since the 1970s, these questions have attracted the attention of an ever-growing number of physicists. As Kadanoff eloquently put it:

> Physicists have begun to realize that complex systems might have their own laws, and that these 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 towards nature's more complex and "chaotic" manifestations, and to attempt to construct laws for this chaos (Kadanoff, 1986: 67 and 1993: 403).

Two significant trends can be discerned: the study of chaos and the study of disordered systems. A common feature of both studies is the deeper understanding of "chance" and "randomness" that has been obtained.

If Anderson made condensed matter physics and other areas of physics as "fundamental" as elementary particle physics, the use of the computer made the study of nonlinear systems and the phenomena they exhibit a practical possibility. In particular, the use of high-resolution computer graphics made it possible for computational physicists to identify and explore ordered patterns in these highly irregular phenomena. This approach, combining "numerical experiments" on the computer with mathematical analysis, has given rise to the new interdisciplinary field of nonlinear dynamics.[30] The interaction between mathematics and the sciences has many different aspects. Two of these are modeling and simulation. The formulation of a mathematical model of a system may involve any branch of mathematics in its architecture, construction, testing and evaluation. The simulation of a system denotes the operation of an existing mathematical model for the purpose of prediction or study (Abraham, 1991: 2). Computers have revolutionized simulation: although they have not replaced classical analysis, numerical computation and graphical representation have become the dominant methods of simulation.[31] And they may also be revolutionizing mathematics by challenging the usual concept of what constitutes a proof.[32]

NOTES

In a panel discussion on "The Future of the Physical Sciences", which took place on April 1961 on the occasion of M.I.T. centennial celebration.

2 It should be stressed that the conceptual – idealistic – component in the reductionism takes precedence over the materialistic one of reducing the number of so-called elementary particles.

3 Thus, in 1954, Feynman had written to Landau:

> it is a remarkable achievement in less than 30 years after quantum theory was discovered we can say that, as far as we know, the qualitative explanation of all extra-nuclear phenomena are understood as a consequence of that theory with two exceptions. One is gravity, which we believe cannot be understood in terms of the simple Schrödinger equation. The other is superconductivity. There remains that one point still resisting siege! (I omit the phenomena of life because we don't know enough about the atomic arrangement to know if quantum theory will hold up) (Feynman Papers. Cal. Tech Archives).

Prior to the explanation of superconductivity by BCS, there was always the nagging possibility that quantum mechanics broke down at distances of the order of 100–200 Ångstrom. Calling quantum mechanics "finalized" should not be interpreted as meaning that all interpretative questions have been answered. The collapse of the wave function during the act of measurement, decoherence, how the irreversibility in the act of measurement comes about, the relevance of consciousness in measurements (and its quantum mechanical "explanation") all remain hotly contested issues.

4 It should be emphasized that in my use of the term "hierarchical layering" the emphasis is on the layering, and that "hierarchical" refers to the fact that some ordering of the layers is possible: in physics, according to the energy scale involved (as set by the masses of the particles that appear in the theory); in biology according to whether one is dealing with individuals, species, genera, etc. (with the caveat that what constitutes a species, genera, etc. may in fact be ambiguous).

5 Forman points to the adoption of anthropocentric and ecocentric ("systems") criteria of significance (in contrast with the emphatically anti-anthropocentric and reductionistic program of modern science), and to the new significance attached to the ubiquitous, as pivotal distinguishing features of the new metaphysics. See also Mirowski (1992).

6 See Guth and Steinhardt (1990), Linde (1990) and Halliwell (1992).

7 In a brief essay entitled "One, Two, Three: Kantian Categories" written in the summer of 1886, Peirce stated that:

> We must therefore suppose that an element of absolute chance, sporting, spontaneity, originality, freedom, in nature. We must further suppose that this element in the ages of the past was infinitely more prominent than now, and that the present almost exact conformity of nature to law is something that has been gradually brought about. We have to suppose that in looking back into the indefinite past we are looking back towards times when the element of law played an indefinitely small part in the universe (Peirce, 1992: 243).

See also Boutroux (1874, 1895) and Mayaud (1986); also Ruby (1986).

8 Recall Pierce's observation:

> If we could find any general characteristic of the universe, any mannerism in the ways of Nature, any law everywhere applicable and universally valid, such a discovery would be of such singular assistance to us in all our future reasoning, that it would deserve a place almost at the head of the principles of logic. On the other hand if it could be shown that there is nothing of the sort to be to found out, but that every discoverable is of limital range, this again will be of logical importance. What sort of conception we ought to have of the universe, how to think of the *ensemble* of things, is a fundamental problem in the theory of reasoning (Peirce, "The Order of Nature", In *The Essential Peirce*, Vol. 1, p. 171).

9 See e.g. Papadimitriou (1993), Svozil (1993) and Traub (1991); also Gell-Mann (1994).

10 See Parisi (1991, 1992, 1993). Since the late 1960s the study of disordered systems, for which the laws governing their time evolution have components chosen randomly, have occupied the attention of an increasing number of theoretical physicists. An example of a disordered system is what has become known as a "spin glass". A spin glass is a disordered magnet. In a typical case, half of the bonds between two spins are ferromagnetic, while the others are antiferromagnetic; which of the bonds are ferromagnetic and which are antiferromagnetic is determined randomly. More generally, random, in this context, means that the position and kind of bond between pairs of spins are distributed according to a probability distribution (to be specified).

[11] R. Descartes: Preface, *Principles of Philosophy*.
[12] See, in this connection, the important writings of C. Chevalley on Kepler, Galileo, Pascal and Descartes and the bifurcation in the metaphysics of science at the beginning of the seventeenth century.
[13] Lepton is the generic name for electrons, muons and tau particles, and their associated neutrinos.
[14] Quantum mechanics indicates that structured systems can only have discrete states, each having a characteristic energy.
[15] For an illuminating account of cosmogenetic theorizing until the end of the nineteenth century see Poincaré (1913a).
[16] Hale added:

We are now in a position to regard the study of evolution as that of a single great problem, beginning with the origin of the stars in the nebulae and culminating in those difficult and complex sciences that endeavor to account, not merely for the phenomenon of life, but for the laws that control a society composed of human beings (Hale, 1908: 3).

[17] On Lockyer see the entry in the *DSB* and the references cited therein; *ibid.* for Crookes. For Crookes's theory of the formation of the chemical elements see, in particular, Crookes's presidential BAAS address in 1886: Crookes (1886); See also d'Albe (1923).
[18] For an account that places Lester Ward in context see Bannister (1987).
[19] In particular, the work of Saha that elucidated the degree of ionization of atoms as a function of temperature, and the experimental work that helped identify the emission and absorption lines of ionized forms of the elements in stellar atmospheres and more specifically in the chromosphere of the sun.
[20] The smaller the size of the system, the greater is the scale of characteristic energies. The excitation energies of the valence electrons of atoms, whose sizes are of the order of 10^{-8} cm, are of the order of electron-volts. The vibrational and rotational spectrum of molecules, composite systems made up of atoms, have characteristic energies of a tenth and hundredths of an eV, respectively. Nuclei, which have radii of the order of 10^{-13} cm, have characteristic excitation energies ranging from thousands (keV) to millions of electron-volts (meV). In all composite systems made up of electrically charged particles, the exited states tend to have short lifetimes. They decay to the stable ground state by emitting electromagnetic radiation.
[21] See, in this connection, the interchange between Weinberg and Mayr on the limits of reductionism: Weinberg (1987b).
[22] This distinction has been emphasized by Dr. Alexi Assmuss, personal communication.
[23] Note that there is a new meaning to a phenomenological description in quantum mechanics.
[24] Low energy here means energies such that the nucleons move nonrelativistically, and well below the threshold for meson production.
[25] It is critical to note that the masses and the charges of the particles that appear in the "specific" Hamiltonians describing particular systems are *phenomenological* parameters that are determined empirically.
[26] Wilson obtained his important insights from the work of condensed matter physicists attempting to explain phase transitions – in particular, the researches of Lars Onsager, David Widom, Leon Kadanoff and Michael Fisher.
[27] See, in this connection, Peter Galison's (1995) insightful paper on the history of string theory and its practitioners.
[28] The effective Lagrangian for that level.
[29] Think of Newton's laws of motion, Maxwell's equations, the Einstein general relativistic field equations, Schrödinger's equation and the Weinberg–Salam theory of electroweak interactions, QCD.
[30] But recall Ulam's quip: "Calling the subject nonlinear dynamics is like calling zoology 'nonelephant studies' "(Gleick, 1987).
[31] The capabilities of modern computers and the computer graphics they can support allow simulations of complex systems of moderate complexity to be carried out. Qualitative and quantitative laws have actually been extracted from such modelling.
[32] See Chaitin (1982).
[33] See Nambu (1991). The concept of dynamical symmetry breaking was brought into elementary particle physics from many-body physics. See Brown and Tian Yu Cao (1991).

[34] See e.g. Abbott and So-Young Pi (1986); Guth and Steinhardt (1990); Linde (1990).
[35] There are obvious caveats, in that the scenario hinges on the Higgs mechanism and the inflationary cosmology is not without its problems, the cosmological constant being one of them. See e.g. Abbott (1988).
[36] Peirce's insistence on an "absolute" characterization of chance is part of his commitment to realism, and indicates that although he did not believe in immutable, absolute, laws of nature, he did believe in spontaneity, or absolute chance, as an ontological element of nature. The "new metaphysics" is much more inclined to what Andy Pickering has characterized as pragmatic realism.
[37] Poincaré (1911); reprinted in Poincaré (1913a). This contains the full essay including the very important mathematical parts which are not contained in the translation: "The Evolution of Laws", in Poincaré (1963: 1–13).
[38] Wheeler at the 1971 Trieste conference honoring Dirac presented a paper "From Relativity to Mutability" (Mehra, 1972: 202–247). He has continued exploring these radical lines; see his essays in *At Home in the Universe* (Wheeler, 1994).
[39] Linde similarly describes bubbles of different universes within an encompassing Metaverse, each with a different gauge group determining the particle physics interactions and their coupling constants.
[40] S. Glashow: "Does Quantum Field Theory Need a Foundation?" lecture, Boston University, 1 March 1996.
[41] For example, condensed matter physicists engaged in the design of new materials such as high Tĉ superconductors.
[42] See, in particular, the chapter on Peirce and Dewey in Bernstein (1971).
[43] I am here outlining the views put forth by Jed Buchwald and myself in Buchwald (1995).
[44] We are here paraphrasing Pickering (1995: 6).
[45] See Galison and Pickering in Buchwald (1995). Using the metaphor of the scaffolding, Pickering would stress the difficulty of alignment; Galison on the other hand would point to the rigidity and, therefore, to the constraints imposed by the scaffolding.
[46] Indeed, it is at times the confluence – the intertwining – of a quasi-stable ontology, a quasi-stable theory, a quasi-stable laboratory practice and particular quasi-stable styles of reasoning (as in the case of the domain described by non-relativistic quantum mechanics) that gives to certain scientific disciplines a special robustness.
[47] It should be emphasized that a commitment by the practitioners of these disciplines to ontological realism has proven enormously fruitful and productive, and that this psychological conviction is an important component in guiding research.
[48] This in contrast to the classical view that saw imagination as the capacity of producing copies of sensible objects, as the capability of imaging, or to the romantic view that considered imagination as an irrational, creative power capable of generating novelty.
[49] In the final discourse at the centennial celebration of the NAS, Rabi pointed to this aspect of science as one of its greatest attractions. Rabi's depiction of the community was as follows:

Members of this community possess an inner solidity which comes from a sense of achievement and an inner conviction that the advance of science is important and worthy of their greatest effort. This solidity comes in a context of fierce competition, strongly held conviction, and differing assessments as to the value of one achievement or another. Over and above all this too human confusion is the assurance that with further study will come order and beauty and a deeper understanding (I.I. Rabi, "Science in the Satisfaction of Human Aspiration", in *The Scientific Endeavor: Centennial Celebration of the National Academy of Sciences* (New York, The Rockefeller Institute Press, 1963).

[50] See Baumann (1994).

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