Complexity Reality and Scientific Realism

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‘Complexity Reality and Scientific Realism’ (an article)

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Abstract

We introduce the notion of *complexity*, first at an intuitive level and then in relatively more concrete terms, explaining the various characteristic features of complex systems with examples. Outside the field of algorithmic complexity, there is no precise and formal definition of complexity that has gained general acceptance, and one has to understand what the term stands for through a number of key notions relating to complex systems. There exists a vast literature on complexity, and our exposition is intended to be an elementary introduction, meant for a broad audience.

Briefly, a complex system is one whose description involves a hierarchy of levels, where each level is made of a large number of components interacting among themselves. The time evolution of such a system is of a complex nature, depending on the interactions among subsystems in the next level below the one under consideration and, at the same time, conditioned by the level above, where the latter sets the context for the evolution. The levels 'below' and 'above' are similarly described. Generally speaking, the interactions among the constituents of the various levels lead to a dynamics characterized by numerous characteristic *scales*, each level having its own set of scales. What is more, a level commonly exhibits 'emergent properties' that cannot be derived from considerations relating to its component systems taken in isolation or to those in a different contextual setting. In the dynamic evolution of some particular level, there occurs a self-organized emergence of a higher level and the process is repeated at still higher levels.

The interaction and self-organization of the components of a complex system follow the principle commonly expressed by saying that the 'whole is different from the sum of the parts'. In the case of systems whose behavior can be expressed mathematically in terms of differential equations this means that the interactions are *nonlinear* in nature.

While all of the above features are not universally exhibited by complex systems, these are nevertheless indicative of a broad commonness relative to which individual systems can be described and analyzed. There exist measures of complexity which, once again, are not of universal applicability, being more heuristic than exact. The present state of knowledge and understanding of complex systems is itself an emerging one.

Still, a large number of results on various systems can be related to their complex character, making complexity an immensely fertile concept in the study of natural, biological, and social phenomena.

All this puts a very definite limitation on the complete description of a *complex system as a whole* since such a system can be precisely described only contextually, relative to some particular level, where emergent properties rule out an exact description of more than one levels within a common framework.

We discuss the implications of these observations in the context of our conception of the so-called *noumenal* reality that has a mind-independent existence and is perceived by us in the form of the *phenomenal* reality. The latter is derived from the former by means of our perceptions and interpretations, and our efforts at sorting out and making sense of the bewildering complexity of reality takes the form of incessant processes of *inference* that lead to *theories*. Strictly speaking, theories apply to *models* that are constructed as idealized versions of parts of reality, within which inferences and abstractions can be carried out meaningfully, enabling us to construct the theories.

There exists a correspondence between the phenomenal and the noumenal realities in terms of *events* and their *correlations*, where these are experienced as the complex behavior of systems or entities of various descriptions. The infinite diversity of behavior of systems in the phenomenal world are explained within specified contexts by theories. The latter are constructs generated in our ceaseless attempts at interpreting the world, and the question arises as to whether these are reflections of 'laws of nature' residing in the noumenal world. This is a fundamental concern of *scientific realism*, within the fold of which there exists a trend towards the assumption that theories express *truths* about the noumenal reality. We examine this assumption (referred to as a 'point of view' in the present essay) closely and indicate that an alternative point of view is also consistent within the broad framework of scientific realism. This is the view that theories are domain-specific and contextual, and that these are arrived at by independent processes of inference and abstractions in the various domains of experience. Theories in contiguous domains of experience dovetail and interpenetrate with one another, and bear the responsibility of correctly explaining our observations within these domains.

With accumulating experience, theories get revised and the network of our theories of the world acquires a complex structure, exhibiting a complex evolution. There exists a tendency within the fold of scientific realism of interpreting this complex evolution in rather simple terms, where one assumes (this, again, is a point of view) that theories tend more and more closely to truths about Nature and, what is more, progress towards an all-embracing 'ultimate theory' – a foundational one in respect of all our inquiries into nature. We examine this point of view closely and outline the alternative view – one broadly consistent with scientific realism – that there is no 'ultimate' law of nature, that theories do not correspond to truths inherent in reality, and that successive revisions in theory do not lead monotonically to some ultimate truth. Instead, the theories generated in succession are *incommensurate* with each other, testifying to the fact that a theory gives us a perspective view of some part of reality, arrived at contextually. Instead of resembling a monotonically converging series successive theories are analogous to *asymptotic series*.

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Complexity and reality: introduction

Complexity is all around us all the time but is something that has come under the lens of focused scientific inquiry in relatively recent times, in contrast to systematic and sustained investigations on *idealized* or *simplified* systems. Simplification is the name of the game, and quite understandably so.

When faced with complex systems that defy our understanding and baffle us, we seek out relatively simple parts of those, whose behavior can be probed and explained with material and intellectual means within our reach. Even this requires stupendous and prodigious efforts of intellect that mankind has not been found to be lacking in. However, there is no hard and fast demarcation line between 'simple' and 'complex' systems, and the human mind has, throughout history, taken up challenges from both the simple and the complex – the former in more precise and rigorous terms and the latter more qualitatively and phenomenologically.

To start with, a simple system is imagined to be isolated from the rest of the world so that the mechanism underlying its behavior can be specified unambiguously. The influence of the rest of the world is then postulated, again in simplified and unambiguous terms, which means that only certain special classes of influence can be included in the theory. The resulting behavior is then determined, but this time only in approximate terms, since an exact determination is often beyond reach. This is essentially how a *model* of some part of the world is built, where simplification and idealization rule the show.

But the world around us is fundamentally complex, and every time mankind has triumphed in formulating exquisitely devised theories about systems, complexity has raised its head, making necessary a fresh look at things so as to account for incongruities arising from phenomena that were left unexplored at the earlier stages. This goes on and on .... like a recurrent process that never approaches conclusion.

Of course, one can be philosophical and say – in tune with a number of great minds in history – that the task of science is to seek out simplicity out of apparent complexity – and that the world is fundamentally simple, ruled by an all-pervading harmony. The position I am going to adopt in the present essay is at odds with the last part of the above proposition. On the other hand, it is indeed true that much of our scientific endeavor consists of an effort at locating relatively simple features in complex systems, in terms of which one gains leverage in understanding and explaining the latter. The simple features provide us with foothold for surveying the complex landscape that lies around and for planning for the next phase of journey, looking for more of such footholds. Simplification and idealization is a necessary strategy in this complex world of ours, made up of complex parts. Indeed, the world uncovers its complexity to us in stages, all the while deceiving us into thinking that the ultimate secret lies round the corner. This is something that will demand our attention later in this essay.

The *theory of complexity* has had a long history but is still an emerging one. We will not go into the history here, nor shall we go through the various aspects of that theory in technical terms. My job in the first part of this essay is to briefly outline a number of major features considered to be common to numerous complex systems of interest. These will then be made use of as a backdrop in addressing issues regarding *reality* and *scientific realism* in the second part.

Complexity: a brief outline

Complex systems: decomposability

Generally speaking, a complex system is made of a large number of components, or *subsystems*, where the subsystems interact with one another, and where *each subsystem is often a complex system* in its own right. Thus, one finds nested levels of complexity forming a hierarchy, where each level corresponds to a complex system, with levels below and above it (the terms ‘below’ and ‘above’ are for convenience of reference only) making up the hierarchy and where, generally speaking, a system at any specified level constitutes a subsystem of the one above.

The systems and subsystems need not be ones located in our familiar three dimensional space. For instance, every individual possesses a vast set of *beliefs* that interact with and influence one another while a belief itself is made up of a relatively large number of *concepts*. A concept in turn involves a number of other concepts, some of which may relate to *objects*, while the concept of an object is generally made up of a number of *attributes*. All these may be located in some abstract *conceptual space* (see [19] for background), whose relation with our familiar *physical* space is non-trivial.

The interactions among the subsystems of a complex system may be rich and varied. For instance, in a big business organization, there may be a hierarchy of management levels, each level being made up of a number of departments. The relations between the various departments belonging to any given level may differ widely, depending on their type. Thus, the exchanges between an accounts department and a purchase department are way different as compared with those between the former and a personnel department. It is not uncommon to encounter a complex system whose subsystems have a *wide spectrum* of interactions.

However, despite these rich and varied interactions, it often makes sense to refer to the subsystems individually and severally, i.e., in other words, the subsystems retain a measure of identity. This is expressed by saying that a complex system is *decomposable* ([26]). On the other hand, this decomposability is only approximate and need not mean that the interactions among the subsystems are not of much consequence. Indeed, it is precisely these interactions that gives a complex system its very own identity, including the way it evolves in time, passes through phases of stability and instability, and generates new levels of organization. Looking at a growing fetus, its course of development into an adult depends on the interactions among its rudimentary bodily organs and the myriads of cells making up its body, along with the genetic and epigenetic interactions at the molecular level within the cells – in addition, its interactions with surrounding systems, such as sources of nourishment, are also of great relevance.

In respect of the *theory* describing a complex system (say, ‘S’), the particular level at which its subsystems are located (with levels above and below it often forming a nested hierarchy) is pertinent to that theory. Such a theory depends crucially on the correct formulation of the interactions between the subsystems in the level located below the one (call it ‘L’) in which ‘S’ is located, while other systems located in level ‘L’ and the ones above constitute the *context* of that theory. For instance, the properties of a solid are determined by the interactions among the atoms or molecules making it up, while these interactions, in turn, are determined by the disposition of the electrons and the nuclei within the atoms. The various macroscopic systems with which the solid exchanges energy and matter, such as large heat reservoirs (the atmosphere, for instance) set the context in which the properties of the solid (such as its thermal expansion and contraction) are expressed. Once again, this distinction between the essential ingredients and the context in respect of a theory is, to some extent, arbitrary but is useful nonetheless.

In summary, a complex system is generally made up of a large number of subsystems, with the latter interacting with one another in intricate ways. The system, in turn interacts with other complex systems forming its environment, while all these complex systems (the system under consideration and those forming its environment) act as subsystems of a complex system at a higher level. Depending on the context, the hierarchy of systems may be assumed to be terminated at some specified stage, with the levels higher up or lower down not being relevant in respect of the behavior of the system under consideration.

Behavior patterns of complex systems: CPS and CAS

The interactions among the subsystems of a complex system and those with various other systems (ones constituting the level higher up in the hierarchy) are generally of the *nonlinear* type, for which the rule *the whole is different from the sum of the parts* applies. This is not a very precise statement but appropriately sums up a number of features observed for actual systems.

For instance, consider a system made up of three subsystems, say, ‘A’, ‘B’, and ‘C’. If the behavior of the combination of ‘A’ and ‘B’ is known, along with the behavior of each of the combinations ‘A’,‘C’ and ‘B’,‘C’ (at times, the three combinations behave in analogous manners), then one cannot infer the behavior of the combination of all three taken together from the properties of the pairwise combinations and from those of the individual systems under consideration. In other words, the presence of additional systems makes a notable difference. Suppose ‘A, ‘B, and ‘C’ are three persons of known temperament and mental disposition, and also suppose that the behavior of ‘A’ in the presence of each of ‘B’ and ‘C’ is known. This may prove to be utterly inadequate in explaining the behavior of ‘A’ in the presence of ‘B and ‘C’ taken together (‘A’ may exhibit friendly or neutral behavior toward ‘B’ but may show loving considerations toward ‘C’; on the other hand, ‘A’ may be found to be seething with suppressed emotions in the presence of both ‘B’ and ‘C’, and may even exhibit some degree of belligerence towards ‘B’ because of ‘C’ apparently ignoring the presence of ‘A’).

Described in general terms, the behavior of a complex system made up of numerous subsystems turns out to be *non-trivial in a major way*. In this context, one distinguishes between *complex physical systems* (CPS) and *complex adaptive systems* (CAS), as highlighted in [14].

A CPS is made up of elements or subsystems that have fixed properties – the molecules of a gas, the spins in a magnetic lattice, or the parts of an automobile. A subsystem can be in any one of a fixed set of states, where a state can change under the interaction with other subsystems belonging to the CPS – often the ones that, in some sense, are ‘close’ to the subsystem under consideration. The position and momentum of any particular molecule in a gas get modified by interaction with other molecules in its close vicinity, while the effects of distant ones are usually small.

In contrast, the properties of elements making up a CAS get changed in the presence of other elements and of other systems interacting with these. For instance, the ability of a gene to express itself as a sequence of amino acids may change under the influence of reactants around it. The elements of such a system – commonly referred to as *agents* – ‘learn’ or ‘adapt’ themselves as they interact with other agents.

The ability of the elements of a CAS to adapt themselves leads to quite amazing behavior exhibited by such systems – often in the nature of *goal-directed* processes, such as the self-replication of genes, or the making of *decisions* by the human mind. To be sure, a CPS may also behave in a 'purposeful' manner, such as a cellular automaton devised in early days by von Neumann that could be made to replicate itself, and a vast number of cellular automata designed subsequently. The difference between such CPS with strange behavior and CAS with adaptive elements often lies in the way these systems are generated – while the purposiveness of a CPS is given to it by some kind of human intervention (a 'programming'), a CAS usually evolves in virtue of its own dynamical characteristics where, at some level deep down the hierarchy, CPS elements (complex molecules, for instance) may be found to play a crucial role. In other words, the learning or adaptive abilities of a CAS may appear as *emergent properties* of assemblies of CPS (example: biological evolution emerging from pre-biotic evolution). The important issue of emergent properties in complex systems – considered to be problematic one by numerous scientists and philosophers – will be taken up in a later section of this paper.

> In the present essay, we will not refer in any major way to the fascinating behavior patterns of complex adaptive systems (CAS), and will mostly confine ourselves to examples and illustrations relating to complex physical systems. In particular, our considerations in the second part of the essay will mostly focus on CPS in order to explain the nature of scientific theories in relation to our experienced reality.

It is difficult to exhaustively categorize – item by item – the extremely rich and diverse behavior patterns of complex systems. Even the more notable ones like the appearance of emergent properties become somewhat elusive when one attempts to pin these down to precise formulation. This does not mean that the various behavior patterns themselves are figments of imagination – the very complexity of the systems prevents an unambiguous and universally valid characterization of these behavior patterns. We will first take up the case of apparently simple systems whose time evolution is described by means of *differential equations*.

The rich and intricate behavior patterns of a complex system often appear in the form of impenetrable perplexities in the cause-effect relationship that it exhibits. A 'small' or insignificant 'cause' often leads to quite dramatic 'effect' as observed in bifurcations and the 'butterfly effect' (sensitive dependence on initial conditions) in nonlinear systems, or in a 'small' change in environmental conditions leading to the eventual emergence of a new biological species. Commonly, a small or 'negligible' cause is found to lead to notable effects because of the role of factors hidden in the depths of complexity of the system under consideration or of context effects (erroneously) assumed to be of no consequence. Thus, a few grains of sand added to a sand-pile may cause the latter to collapse because of the fact that it was close to *criticality* to start with. Analogous intricacies and puzzles are met with in respect of emergent properties of complex systems.

Complex systems: nonlinear dynamics

Numerous complex physical systems (CPS; the subsystems making up a CPS are not adaptive in nature) are described in terms of *differential equations* where these equations are, generally speaking, of the *nonlinear* variety (linear systems are, in a sense, exceptional though these are familiar, well-studied, and useful too).

> The differential equations may describe the time evolution of a finite number (say, N) of variables making up a N-dimensional *phase space*, where these belong to the class of *ordinary* differential equations. More generally, a system may be described by a number of *fields*, such as the velocity field of a fluid, in which case the behavior of the system is described by a set of *partial differential equations*, representing the time evolution in an *infinite* dimensional phase space. Once again, the partial differential equations are generally speaking, nonlinear ones, though linear partial differential equations, on which a vast literature (in physics and mathematics) exists, are also of great relevance. The *Navier-Stokes* equations describing the flow of a fluid constitute a well-known example of a set of nonlinear partial differential equations in physics.
>
> A set of ordinary or partial differential equations in a (finite- or infinite-dimensional) phase space is said to describe a *flow* in that space. Alternatively, one can consider a *mapping* in the phase space describing the evolution in *discrete* time-steps. In the context of the present essay we will refer mostly to nonlinear ordinary differential equations in phase spaces of relatively low dimensions ($N = 2, 3, \cdots$).
>
> Let $x_1, x_2, \cdots, x_N$ be the variables describing the *state* of a system at any given instant of time. Such a state is represented by a point in its (N-dimensional) phase space. Subsequently, the

> state will *evolve* in time in accordance with the set of differential equations under consideration, describing a *trajectory* in the phase space. While such a trajectory is a continuous one, the time-evolution of a system described by a mapping is represented by a discrete succession of points, representing the succession of states at discretely spaced time instants.
>
> While nonlinear differential equations (mappings will also be occasionally referred to) will be seen below to generate complex behavior, linear systems are, typically, *simple* ones obtained as limiting cases from nonlinear systems. The term ‘simple’, however, need not imply that the behavior of such systems can be described trivially and without effort – these being of enormous relevance in *models* studied in all branches of natural science. A field in which a set of linear partial differential equations describe a real-life system (and not simply an idealized model) is *electromagnetic theory* where the *Maxwell equations* describe the space-time dependence of an electromagnetic field. Great mathematical difficulties are encountered (and often dealt with by invoking *approximation schemes*) in virtue of *boundary conditions* of various types, relevant to specific problems.
>
> In contrast to systems represented by nonlinear differential equations that serve as mathematical models of complexity, ones represented by linear differential equations can be described as ‘simple’, though not in the sense of ‘easy to analyze’.

Nonlinear equations do not conform to the *principle of superposition*, and serve as illustrations of the rule expressed qualitatively as ‘the whole is different from the sum of parts’. No general principles exist for the construction of solutions of nonlinear differential equations, and the infinite diversity and variety in the time evolution of systems described by these equations remains largely unexplored. Nonetheless, deep insights have been developed regarding various *types* of behavior that these systems follow. The *qualitative theory* of nonlinear systems was developed by Poincare and other great mathematicians in the first quarter of the last century. Their investigations were carried forward in large strides by others during the second half of the century, resulting in a highly developed theory that is far beyond the scope of the present essay.

In describing the various types of behavior of a system represented by a set of nonlinear differential equations one generally looks at the *large time* regime, i.e., the one in which the *transient* behavior, if any, is not of relevance, and the system exhibits a behavior pattern that is termed ‘asymptotic’. Speaking schematically (i.e., not entering into a precise classification, which is fraught with difficulties anyway), this long-term or asymptotic pattern may correspond to a time-invariant state, an oscillatory state, a quasi-periodic state, or to *chaotic* behavior.

> A quasi-periodic state is a generalization of a periodically varying one, where the time-dependence of the relevant state variables involves several frequencies, incommensurate with one another.

There exist several quantitative indicators of chaotic time evolution. In other words, there may be numerous different *types* of chaos. The indicators of chaos are mostly based on various *entropy* measures (see, for instance, [28]; see also [13]). It seems extremely likely that the generic behavior of nonlinear systems involves chaotic time evolution.

In a chaotic time evolution, either the whole phase space or some part of it is explored (by the point representing the state of the system) in a random manner. In contrast, time-invariant, periodic, and quasi-periodic behavior patterns are referred to as *regular* ones.

> In the thermodynamic description of systems, one distinguishes between *microscopic* and *macroscopic* states and their time evolution. In the macroscopic description one often encounters an equilibrium state which is time-invariant, while the same system, when described in microscopic terms, may involve chaotic dynamics in the relevant part of the phase space (see, for instance, [12]).

The description of a nonlinear dynamical system may involve a number of characteristic *parameters*. For instance, in the case of a fluid flowing through a pipe, the nature of the flow may depend on the *coefficient of viscosity* and density of the fluid, the diameter of the pipe, and the pressure difference between the ends of the pipe driving the flow.

For a given set of values of the parameters, different parts of the phase space may correspond to various different behavior patterns. Thus, depending on the *initial condition* the system behavior may turn out to be either time-invariant or periodic (or even quasi-periodic) in defferent regions of the phase space. Additionally, what is remarkable in the case of a nonlinear system is that, for various different sets of values of the characteristic parameters, the system may undergo *qualitative* changes in the behavior pattern. Such a change is generally referred to as a *bifurcation*, though here again there remains a big gap in precision since it is not easy to classify various possible types of bifurcation (there are, for instance, *local* and *global* bifurcations or, again, bifurcations in conservative and dissipative systems, bifurcations with various possible *codimensions*, and so on).

Even a system with a phase space of a low dimension (as low as one in the case of mappings and three in the case of flows) can have a complex behavior pattern as it evolves in time. In other words, the complexity of such a system seemingly resides in its time course of evolution, while this complexity in time evolution may reflect a complexity n the underlying structure of the system itself.

> In an early and influential paper by Robert May([21], one encounters complexity in apparently very simple systems (idealized biological populations) evolving in discrete time (successive generations, assumed to be non-overlapping) through a succession of bifurcations. The parameter whose value controls the bifurcations in this system was related to the rate of production of offspring from one generation to the next. Evidently, this parameter is determined by a large number of factors relating to the life-cycle and reproduction of the species under consideration, the details of which is ignored in the simple set of nonlinear equations describing the population.
>
> Seemingly simple systems exhibiting chaotic time evolution may result from a process of *reduction* from more complex ones, where relevant variables pertaining to the underlying complexity are not explicitly taken into consideration, with the result that the reduced system evolves in a complex manner.

The set of characteristic parameters controlling the bifurcations of a nonlinear system can vary under the influence of other systems that may come in interaction with it. In this context, recall the feature of (approximate) decomposability of a system whose behavior pattern is determined by subsystems at a lower level belonging to a hierarchy of levels, while the same behavior is also conditioned by interactions of systems at the same level(say a number of biological populations interacting with one another) and by levels higher up. Because of the conditioning effects of the higher levels, the parameters characterizing the dynamics of a system do not remain ideally constant, and keep on changing slowly in time, causing an unfolding of bifurcation scenarios whereby the behavior pattern of a system keeps on undergoing qualitative changes.

In a number of situations involving real-life systems, these qualitative changes in the time course of evolution appear in the form of *emergent properties* ([14]) and and *self-organized complexity* ([29], [15]). It is to be mentioned, however, that the appearance of these novelties is not entirely the consequence of intrinsic properties of a system, since these critically require an appropriate *context* in the form of an influence of external systems – ones in the same level of the hierarchy of complexity pertaining to the system in question or in levels lying above. For instance, referring to the microscopic dynamics of a macroscopic system, the emergent phenomenon of a phase transition requires an appropriate condition, say, one involving the temperature in the case of a magnetic lattice where the dynamics decomposes into two *ergodic* components.

> The term ‘self-organized complexity’ means the proliferation of structures at various scales in the course of time evolution of a complex system. At times, the emergence of such structures occurs under some kind of *driving* by external systems, but then one can think of an augmented system including the external systems in question, in which the said structures emerge spontaneously, i.e., in virtue of its own dynamics (hence the qualifying phrase ‘self-organized’). A commonly occurring scenario in which self-organized complexity is found to appear is that of *self-organized criticality* where there occurs a loss of stability under a relatively *slow* driving and the rapid transition to a stable configuration. However, such difference in time scales is not a necessary condition for the spontaneous appearance of structures in complex systems.

The appearance of novelty in a system described by a set of nonlinear differential equations occurs as a consequence of *de-stabilization* of an existing stable behavior-pattern in the phase space and the attendant emergence of a new stable configuration or pattern. Often, one finds a succession of such transitions in an unfolding chain of ordering phenomena. For instance, in the case of fluid flow under dissipation (i.e., heat conduction and viscous effects), say, in the case of heating of a layer of fluid from below (against the pull of gravity), one observes a transition from steady conduction to non-steady motion involving convective rolls of a succession of various geometric forms and then, ultimately, to *turbulent motion*. The characteristic parameter controlling the transition from one type of flow to the next in this case is termed the *Rayleigh number*, and the appearance of a succession of variously shaped convection cells associated with increasing values of this parameter constitutes an instance of self-organized complexity.

Complexities of time evolution

The successive regimes of *instability* and *stability* commonly associated with nonlinear differential equations are found to be present in complex systems of more general descriptions (e.g., in complex adaptive systems) where a precise mathematical description in terms of differential equations may not hold. In electronic control systems these regimes of instability and stability are associated with *positive* and *negative feedback* between various different parts of a circuit. Generally speaking, instability and stability (of *local* and *global* varieties) are consequences of the large number of subsystems making up a complex system (at some specified level in a hierarchy of complexity) and the spectrum of interactions between these subsystems.

It may be mentioned here that the complex and chaotic time evolution of a system may, under certain circumstances, be related to *computational* or algorithmic complexity [14] encountered in computation theory. For instance, for a system with positive *Kolmogorov-Sinai entropy* [12], if one tries to describe computationally a long time series characterizing a trajectory of the system or to specify as accurately as possible the initial condition in the phase space giving rise to the trajectory then the length of that description diverges along with the time-interval of evolution.

Thus, a complex system, in virtue of being composed of a large number of subsystems with a wide spectrum of interactions between those, and of being a part of a hierarchy made up of various levels exhibits, in general, a complex time evolution, the latter being characterized by several time scales. While we have spoken of the asymptotic regime of time evolution in the case of nonlinear differential equations, one may observe asymptotic behavior in relatively shorter and longer time scales as well, making up a *hierarchy of time scales* along with the hierarchy of levels of complexity mentioned above.

In other words, complexity is manifest *across numerous scales* – both in time and in the phase space, where the latter may be of an arbitrarily large dimension.

Over a limited time horizon, a complex system may exhibit a certain pattern and structure – either in a high dimensional phase space or even in the familiar three dimensional space, such as the patterns of oceanic and air currents in a geographical region. Over a longer time scale, these patterns may give way to currents having different characteristic features. Along with the temporally changing patterns, there are commonly found distinct patterns in various different regions of space (once again, either in the phase space or in spaces of lower dimensions, including the familiar three dimensional space). Such patterns and structures are indicative of the emergence of *order* in space and time.

The intricate and inscrutable nature of the time evolution of a complex system commonly results from *co-evolution* [28] – i.e., evolution not only due to fixed interactions between the constituent subsystems (along with the ubiquitous context effects), but due to changes occurring in the nature of these very interactions, and due to changes in the subsystems themselves. Commonly, this owes its origin to the fact that one cannot separate clearly the intrinsic dynamics from the context – small changes in the environment may trigger an instability. In other words, *everything evolves* and can affect the dynamics in major ways – by way of altering the subsystems, the interactions, and even the context – and the entire evolution becomes an enormous tangle of nested correlations relating to causes and effects. Faced with this tangle, one can at best untie a few knots here and a few knots there – *locally* in space and time, and learn the 'laws' governing the evolution only locally as well. This will engage our attention later, in the second part of this essay.

> Typically, a mathematical formulation of the evolution of a complex system remains a tall order – one describes the evolution at best in the form of an algorithm, and that too as only a partial description. Even when one describes the dynamics in the form of a set of nonlinear differential equations (once again, in the form of a model), the solution to the equations can only be obtained in qualitative terms – for instance, as information pertaining to the structure of certain invariant sets and their stability characteristics, and to their dependence on relevant parameters, while bifurcation scenarios are also obtained numerically. An algorithmic description [28], on the other hand, is usually a flexible one, yielding a lot of relevant information about the system – depending on what one wants to know.

In this context, it is important to distinguish between microstates of a complex system and its *macrostates*, the latter being in the nature of statistical averages or fluctuations of microscopic variables relating to its detailed phase space description. For instance, major breakthroughs in the understanding of complex systems have come about in the form of *scaling* and *power law behavior* relating to macroscopic data, and their dependence on parameters (or data) specifying the *structural features* of the system. A convenient way of representing the latter is in the form of *networks*. All this will be briefly touched upon in the following.

Complex systems as networks

It is often convenient to represent a complex system in the form of a *network*. In this representation, the subsystems making up the system under consideration are said to form a set of *nodes*, to be visualized as dots or circles strewn around in space (we will imagine the nodes to be located in the familiar three dimensional space, though the dimension of the space may not be of much relevance; for instance, the nodes of any finite network may be imagined to lie on a single line). In the case of a CAS, the nodes are often referred to as *agents*. The interactions or correlations among the subsystems are represented in the form of *links* connecting the nodes . If the correlation between a pair of nodes has a sense of asymmetry associated with it then the link is visualized as being a directed one (example: husband-wife relationship in a community); if, on the other hand, the correlation is symmetric then it can be represented by a single link without any direction – or by a pair of oppositely directed links (example: relation of friendship).

The network representing a complex system is, generally speaking, a *multi-layered* one [28] since its nodes may be connected by various different *types of links*. For instance, in a human society, nodes may be correlated in terms of religion, political commitment, family relations, occupation, and so on. These multiple layers constitute an important characteristic determining the nested and tangled structures that appear within a complex system.

The time evolution of a complex system is described by specifying whether and how new nodes are created and old nodes get removed from the system, together with the way new links are established and existing links get removed *and*, additionally, how the layered structure of the network gets modified. All this goes to describe the co-evolution of the system under consideration. Such a description of the evolution of a network may be a deterministic one or may have an element of randomness in it.

> Links in a network often carry *weights* that quantify the strengths of correlation between pairs of nodes. The weights are important in determining how the network evolves, and may themselves co-evolve along with the other network features.

It is often an impossible task to describe the detailed structure of a complex network, though certain features represented by quantitative measures can be identified as being relevant ones in various contexts. For instance, one can talk about the *degree distribution* in a network. The *degree* of a node specifies the number of links attached to it, and is one of its basic properties. It is rare to have a real life network with all nodes of equal degree. More generally, a network with N number of nodes is characterized by the probability distribution $P(k_i)$ $(i = 1, 2, \cdots N,\ k_i = 1, 2, \cdots)$, which gives the probability of a node i (we assume the nodes to be labeled with numbers) to have a degree k_i. The *average degree* of the network is given by $\langle k \rangle = \frac{1}{N} \sum_i k_i$. A distribution carrying somewhat less information is the probability $P(k)$ that any arbitrarily chosen node has a degree

k $(= 1, 2, \cdots)$.

The degree distribution gives the most basic information about a complex network, but is only one among a large number of characteristics indicative of its structure in quantitative terms. The degree distribution gives an indication of the relative importance of the nodes in the network connectivity and dynamics, telling us, among other things, how the important nodes are distributed within the network. A related measure is the *clustering coefficient*, which gives the probability that any two neighbors of a node (i.e., nodes connected to the one under consideration) are also neighbors of each other. A *cluster* in a network refers to a set of mutually connected nodes.

Also of major relevance in describing network structures are concepts relating to *walks and paths* [28]. A walk is a succession of nodes such that each pair of successive nodes is connected by a link. The number of links in the walk, in between its terminal nodes, is referred to as its *length*. Closed walks or *loops* are ones with identical terminal nodes, and provide information about *feedback* in the network. A *path* is a walk that visits no node more than once. The shortest path between a given pair of nodes can be made use of in defining a distance measure on a network.

Without gong further into the issue of structural measures characterizing a network, we now refer to another aspect of network structure, namely whether or not it is a *random* one, a widely referred instance of which was introduced by Erdős and Rényi in early days of network theory, and is known as the Erdős-Rényi (ER) network. In a random network, some or all entries in the *adjacency matrix* (a matrix expressing the connectivity between nodes of a network [28]) are random variables. At times, the entire adjacency matrix can be one drawn from a random ensemble. The class of random networks includes ones in which, as mentioned earlier, the randomness is generated dynamically, where nodes and links can be randomly added or removed, i.e., the elements of the adjacency matrix evolve as stochastic processes.

An ER network (also referred to as an Erdős-Rényi-Gilbert network) with a specified number of nodes is characterized by a fixed (i.e., time-independent) probability (say, p)

of any pair of nodes being connected by a link, independently of other pairs. Various possible realizations of this network may differ in their number of links and in their probabilities of occurrence. In a second type of ER networks, in which the number of links (L) is specified along with the number of nodes (N; the links are picked randomly between pairs of nodes), all realizations are equiprobable in the corresponding ensemble. Though an ER network is of a simple structure, it admits of a *phase transition* analogous to one observed in a percolation problem.

Complex networks, however, are generally not of the ER type, though the ER model often serves as reference in describing the properties of such real-life networks. At times, networks are defined and described by appropriate modifications of the ER rule. Networks differ widely in their characteristics, and a large number of such characteristics are often needed to analyze and understand any given network. Typically, the properties of a complex network are addressed by modeling the underlying network formation process where one specifies the mechanisms that drive the process, i.e., the dynamics of the nodes and links. Since analytical methods do not usually suffice to adequately characterize the resulting network, computer programs are most often resorted to.

Small-world networks

The description and analysis of complex systems in terms of networks is of remarkable value in numerous areas including the one of *social networks*, where it has been employed since early days. Social network analysis has led to the discovery and understanding of a number of features observed in complex systems, such as the *small-world phenomenon*. This phenomenon is observed in numerous complex systems, among which are the ones first described in the celebrated work of Watts and Strogatz. Their approach was to start from a regular network and gradually introduce random links between nodes so as to obtain network structures intermediate between regular and random ones.

Random networks such as the ones of the ER type are characterized by a low degree of clustering and a relatively short separation between pairs of nodes chosen randomly.

Most regular networks, on the other hand, are characterized by high clustering and large separations.

> The separation between a pair of nodes in a network is defined as the smallest number of links to be traversed in succession in moving between the two – if the two are not connected by an uninterrupted chain of links, the separation is defined to be infinite.

> As mentioned earlier, the degree of clustering of a node is defined as the probability that any two nodes linked to it are also mutually linked. On averaging over all the nodes in the network, one obtains the overall degree of clustering in it.

If the links in a regular network are replaced (in a random succession) with links establishing random connection between nodes, one obtains, even with a relatively small number of replacements, a network with high clustering and a *low* separation. It is typically found in the case of social networks that nodes have, on the average, a separation spanning only six links. More generally, networks have the *small-world* property even as these may have only a small degree of randomness in their structure. The small-world phenomenon arises because randomly established links dramatically reduce the separation between nodes (for instance, a link established between previously unconnected nodes reduces the separation from infinity to one). An analogous manifestation of a similar effect is the one referred to as the 'strength of weak ties', where weak correlations between strongly tied clusters result in conspicuous phenomena – often running counter to intuition.

> Network analysis is potentially of great value in understanding how *neuronal aggregates* function in the brain, where effects such as the small world phenomenon are likely to play an important role [27].

Complex systems: scaling and power law statistics

We now briefly mention the features of *scaling* and *power law* distributions in complex systems. A variable y is said to scale as a function of a second variable x if the relation between the two is of the form of a *power law*, $y \propto x^{\alpha}$, where α is referred to as the exponent or the degree of the scaling. Scaling relations are often not exact since the relation between the two variables may be influenced by small effects arising from other relevant factors. Scaling-based arguments are useful in understanding diverse phenomena of interest where some fundamental scaling assumption can be invoked to relate various features of a system in a simple manner, regardless of its complexity. For instance, Galileo established the scaling relation $R \propto L^{\frac{3}{2}}$ (an instance of *allometric scaling*), between the radius (R) of a weight-bearing bone of an animal and the linear dimension (L) of the latter, based on the assumption that the strength of a bone varies as the square of its radius. Scaling relations are remarkable in that they relate diverse feature without direct reference to the details of the system concerned. Of course, not every functional relation pertaining to a system can conceivably be a scaling, but the manifestation of the joint operation of a large number of correlated factors often appears as one.

Scaling is typically associated with *self-similarity*, in virtue of which a system appears similar when observed in various different scales. A homogeneous object is trivially self-similar, while interesting self-similarity properties are exhibited by *fractals*. It is common for a complex system to be generated in a self-similar manner for reasons of economy and adaptability. A remarkable power law relation in biology (another instance of allometric scaling) – corroborated by a large number of observations – is that the metabolic rate of an animal of linear dimension L, when compared with other species of different linear dimensions, scales as $L^{\frac{3}{4}}$ so as to keep them cool. This is explained by noting that, for efficiently transporting metabolites to all the cells in the body, the blood vessels proliferate in a tree-like manner, with branches forming a self-similar pattern. Scaling laws are known to arise in the context of critical phenomena, in which there emerge long-range correlations among components, whereby systems become effectively *scale-free*.

More generally, scaling laws arise in the statistical description of stochastic complex systems where distribution functions (probability distributions of relevant variables) typically exhibit scaling behavior – this contrasts with non-complex statistical systems (ones with non-interacting components or with interactions resulting in a simple network structure) where distribution functions are generally of the exponential type. A large class of distribution functions characterizing complex systems of diverse descriptions includes those of the *fat-tail* type where the distribution has a power law tail. In other words, a fat-tail distribution goes like $f(x) \sim x^{\alpha}$ for large x, where x is a random variable associated with the occurrence of a certain set of events characteristic of the system under consideration, large values of which correspond to rare events in the set. It is likely that the fat-tail phenomenon is associated with interactions among the components of a complex system that conspire to generate events that would be exponentially rare in the absence of interactions. This, however, is not a precise statement, and no general or universal explanation is known for the generation of power-law or fat-tailed distributions, though a number of distinct mechanisms have been observed to lead to such distributions in large classes of complex systems.

Among these we mention here the occurrence of fat-tailed distributions in systems with *self-organized criticality* and those with *sample space reducing* (SSR) processes ([28], chapter 3).

Self-organized criticality is a widely shared feature of systems driven away from equilibrium by external means where a system approaches a critical state and becomes unstable, thereby exhibiting a new behavior. The term ‘self-organized’ refers to the feature that the critical state is approached, in the presence of the driving which need not be precisely controlled, due to the intrinsic interactions among the components of the system. Such critical behavior under driving is observed in the dynamics of a sand pile that gradually builds up when grains of sand are gently dropped on a table-top. On attaining a certain critical slope, the pile collapses as more sand is dropped on it and an avalanche builds up.

The dynamics of the sand pile is dominated by two opposing factors – the slow *driving* by the addition of sand grains, and the rapid *relaxation* by the movement of the grains along the slope of the pile, and is characteristic of a wide class of processes. The slow driving allows the system to find a local equilibrium till a state is reached when the local equilibrium becomes unstable and a rapid relaxation ensues.

Fluctuations in self-organized critical systems commonly exhibit approximate power law statistics in the relevant probability distributions, and the fat-tail behavior is manifested in the form of a relatively high probability of occurrence of avalanche-like events. The slow-driving-rapid-relaxation is commonly observed in geology, weather change, psychological processes, progress of diseases, onset of epidemics, crash in financial markets, and in many other diverse circumstances.

Sample space reducing (SSR) systems provide instances of the emergence of power laws in history-dependent (or *path*-dependent) processes, i.e., ones where the 'memory' of its previous states are relevant in determining the statistics of the system.

> History-dependent processes are commonly observed in driven systems as in the case of linear response theory of non-equilibrium statistical mechanics where time-dependent *response functions* determine the evolution of expectation values of the observables of a system.

In a large class of SSR processes, the size of the sample space (the space of possible states, or behavior patterns – analogous to a phase space) gets altered as a process unfolds, and the statistics relating to the system dynamics becomes history-dependent. A common SSR scenario involves a driving force that takes a system to an 'excited' configuration, from which it relaxes towards an equilibrium state, where there may be a succession of such excitation and relaxation phases, with the system driven permanently out of equilibrium. In a simple model of such a process ([28]), one obtains *Zipf's law* (see below), with the probability of outcome i $(1, 2, \cdots, N)$ (in an initial sample space with outcomes marked $\{1, 2, \cdots N\}$, which then gets reduced at successive stages) given by $p(i) \propto i^{-1}$. Even as one widens the scope of the model, one finds that Zipf's law emerges as an *attractor* for the probability distribution.

More generally one obtains a fat-tailed distribution where, significantly, one can infer numerous details of the driving and relaxation processes from the form of the distribution.

SSR processes are of great relevance in a wide diversity of phenomena in different areas including those in science, sociology and linguistics. For instance, the probability distribution of words in meaningful sentences formed at random can be viewed as an SSR process. In a broad sense, *evolutionary* processes can be understood as being of the SSR type, while an alternative description in terms of self-organized criticality is also possible.

Power law statistics: the Zipf distribution

Perhaps the most widely known instance of power law statistics is *Zipf's law*, which constitutes a special instance of the Zipf distribution that gives the probability distribution of a set of discrete random variables (say, $x_i,\ (i = 1, 2, \cdots)$) as $p(x_i; \alpha) \propto x_i^{-(\alpha+1)}$, where α is a parameter characterizing the distribution.

The Zipf distribution often appears when the random variables x_i correspond to the *rank* in which the outcomes of an experiment appear when arranged in descending order. For instance, let the experiment consist of a count of the populations of a number of cities, with the ranks of the counts arranged in descending order being $1, 2, \cdots$. Repeating the experiment for a large number of sets of cities, one can then work out the relative frequencies of counts corresponding to ranks $i\ (= 1, 2, \cdots)$ and then the probability distribution p_i, which turns out to be of the form $p_i \propto i^{-1}$. This is referred to as Zipf's law.

Zipf's law or, more generally, power law distributions, are commonly interpreted as *emergent properties* (see below) of complex systems. The idea of emergent properties has had the dubious distinction of fueling the controversy between the viewpoints of *reductionism* and *holism* in the philosophy of science. I will put forward my own take on this issue later in this essay. But emergent or not, the validity of Zipf's law can be traced to the rules of constitution of a system (i.e., the ones enumerating or codifying how the system is built up from its elementary constituents, or how these constituents are *correlated* with one another), in a number of instances. Thus, Li [20] demonstrated that Zipf's law emerges as the rank distribution of word frequencies for randomly generated texts simply from the rules of formation of the words and from the assumption that the texts are long sequences of the words.

Complexity and entropy

Complex systems admit of descriptions inherently statistical in nature. This may be due to the stochastic nature of the formation and evolution of a system or due to the fact that all descriptions of a complex system are, by the very nature of things, partial. Accordingly, the quantitative specification of the properties of a complex system is accomplished in probabilistic terms, in which *entropy* plays a central role. Depending on the nature of the system concerned, one or more of three notions of entropy can assume relevance (see [28] for details), namely, *Boltzmann-Gibbs* entropy as defined in statistical mechanics, entropy as *information*, and entropy derived from a *variational principle*.

> All the above three notions of entropy converge in the case of statistical mechanics of equilibrium states of thermodynamic systems where the complexity of a macroscopic system in equilibrium is described in terms of an equilibrium ensemble that specifies the probabilities of microscopic states of the system which, to be sure, is a partial description. However, for non-equilibrium processes, the notion of entropy is not well defined, though one referred to as the *diagonal entropy* in quantum statistical mechanics tuns out to be useful [9].

Among the three notions mentioned above, the one of entropy derived from a variational principle – commonly referred to as the *maximum entropy principle* – can be looked upon as being of relatively more general relevance in the context of complex systems. This principle proves to be extremely useful in the analysis of large data systems (an essential ingredient of modern day civilization with all its inhomogeneities, complexities and inherent turmoil) where *constraints* of various descriptions can be incorporated in deducing various statistical distributions by invoking the variational principle. In this, one uses the approach based on *Lagrange multipliers* – one associated with the name (among others) of E.T. Jaynes in the case of statistical mechanics.

Complex systems: emergent properties

With all this background outlined in the preceding sections, we now focus on the issue of *emergent properties*, widely thought to be the quintessential feature characterizing complex systems. Briefly, the notion of emergent properties tells us that a complex system is structured into various *levels* as in a hierarchy, and each level exhibits behavior that cannot be deduced from the properties of the constituents residing in the immediately lower level ('the whole is essentially different from the sum of parts') – there is novelty appearing at successive levels of the hierarchy. I will submit that, like many other things in life, all this talk of complex systems being characterized by levels and emergent properties is essentially a useful interpretation of our experience relating to complex systems – one that cannot be conclusively proved right or wrong on the basis of hard evidence, but certainly a useful one in the description and explanation of systems and events in various different *contexts*.

One of the most notable instances of emergent properties (the *mother* of them all, if I may say so) is *life*. When compared with isolated molecules, a living being is a most complex object. As per our present understanding (I take lots of liberties here, just to make a point), isolated molecules came together to build up, stage by stage, more and more complex polymers whereby early life-like organelles made their appearance in an oceanic 'hot dilute soup', whose chemical reactions with the atmosphere enveloping the earth at that stage of evolution led to an oxygen-rich environment – thereby ushering in a phase of proliferating life forms. The point of this summary (if at all it may be called one) is to state that there is no *point of discontinuity* in the process of pre-biotic evolution as far as chemical reactions go – all the stages of the evolution were enacted strictly in accordance with the principles governing chemical reactions: *Nature did not know* that a momentous development was happening within its fold – one that would then lead to an even more momentous drama, if there could be one – the biological evolution. It is *our perception* that makes life so stupendously different from non-life.

> One may recall here the principle of 'quantity leading to quality' propounded by by Hegel and emphasized by Marx and Engels ([6]). This deeply philosophical principle has perhaps been

> interpreted and used rather shallowly in subsequent literature.

Does this mean that I deny the enormous degree of *self-organized complexity* that we call life? Absolutely nothing of the sort. But I do maintain that the great distinction between life and non-life is a matter of *perspective*. When we stand back from the enormously complex chains of chemical reactions that occurred during the pre-biotic evolution and the various stages of biological evolution, and the even more complex reactions going on in a human body, and look only at the contrast between an inert cluster of molecules and a vibrant young person, we say that the latter is endowed with emergent qualities. This is the view of holism, which maintains that there is 'something more' in the whole as compared to its inert parts. But then rises the voice of reductionism: looked at from the point of view of the fundamental constituents and their mutual interactions, does a living human body differ from a single protein molecule?

I will not labor the point here but will have to take it up again in the second part of this essay – I can only state here that it is far from my intention or ability to resolve or contribute something new to the controversy between reductionism and holism since each of the two is only a point of view that depends on what perspective one adopts.

> It may appear that I am adopting here the condescending attitude of portraying the viewpoints of reductionism and holism as vacuous and the choice of one over the other as hollow and irrelevant. But that would be unfair on me. All that I want to say is that it is no use trying to *resolve* the controversy relating to the two, or to establish one or the other as the one correct view of nature. Do I then prefer that the two views be *reconciled*? Once again, that would be a misrepresentation. Contrary viewpoints are neither resolved nor ever reconciled, but the very approach based on the *dichotomy* between the two views is fraught with problems. One has to be comfortable with the idea that *both the two* are points of view – Nature does not know if it is amenable to a description in terms of either the reductionist or the holist view – it is just itself and is completely indifferent to what our concepts about it are. Rather than trying to resolve between or reconcile the two seemingly contrary views, a more fruitful approach would be to accept the *indissoluble unity* of the two in our effort to understand nature.
>
> At this point, I offer an analogy chosen from the context of philosophy of mathematics. In the so-called classical philosophy of mathematics and mathematical logic, the law of the excluded middle is accepted as a basic axiom. On the other hand, intuitionistic logic does not accept that

> ‘law’ as a fundamental axiom. It does not accept a statement as either true or false till one or the other is established by rigorous deduction. In other words, it tells us not to tag everything with *either* a ‘yes’ *or* a ‘no’. At the same time, it does *not* assert that there lurks a *third* alternative – something beyond ‘yes’ or ‘no’. But then, I must say no more on the philosophy of mathematics lest I should be putting my foot in my mouth.
>
> In summary, then, the good old Hegelian-Marxian dictum of *unity of opposites* – a great aphorism if ever there was one.
>
> However, aphorisms are meant to be appreciated and marveled at, but they are too enigmatic to be adopted as working principles in the concrete and untiring work people undertake in interpreting nature bit by grinding bit. In other words, ‘unity of opposites’ is one way of looking at and interpreting this world of ours – a useful way as I understand it – more useful, perhaps, than adopting a dichotomous approach in life and in science.

For now, we will adopt the idea of emergent properties as we have adopted the idea of complex systems constituting nested hierarchies earlier. Indeed, it would be a sophistry to deny the existence of levels of complexity and of properties specific to those levels that leave no trace when looked at in the context of a lower level or even in the context of a higher level.

> The question that still remains is how to *interpret* the existence of levels and the emergent properties. I believe this question of interpretation remains largely open (questions of interpretation, of course, are never fully closed), and I will take this up again in section Emergent properties and emergent theories later in this essay. The issue of emergence comes up almost everywhere in any discourse relating to complex systems.

An instance of emergence is provided by the property of *wetness* of water [14], which is a property of water molecules in bulk, that leaves no trace in one single water molecule, because wetness arises in virtue of *interactions* between water molecules.

This is one way of looking at the phenomenon of emergence: an emergent property of a system appears in virtue of interactions between subsystems that populate a lower level of the hierarchy of complexity but is absent in the subsystems looked at individually. Even as this appears to be quite acceptable as a defining characteristic of emergence, I should point out that the idea of identifying an entity (a subsystem in the present context) abstracted from its interactions with other entities is not of much relevance, as I discuss later.

Emergence appears in other contexts as well. For instance, a system described in terms of a set of nonlinear differential equations exhibits bifurcations as some characteristic parameter is made to cross some threshold value (perhaps, due to a slow change induced by environmental systems), in consequence of which there occurs a transformation in the topology of the trajectories in the phase space, with attendant transformations in system properties. In the case of a complex adaptive system (CAS), an analogous transformation may arise due some change in the environment when some individuals in a population become better adapted than the rest and one or more traits specific to these individuals get preferentially transmitted to succeeding generations.

The two scenarios sketched in the preceding paragraphs tell us that emergence appears in situations that are, at least on the face of it, distinct. In one the emergence is due to the assembly of a large number of building blocks that interact among themselves – much like the putting together of letters of an alphabet that produces a meaningful word. One may imagine the process of generating the assembly to be carried forward through steps – words put together to form sentences, sentences assembled to make up a paragraph illustrating a theme, paragraphs put together to form a short story, and so on – perhaps generating a book, and then an entire library. The *other* scenario involves a changing environment inducing a momentous transformation in a system.

A *third* scenario involves a change in the rules of formation of a system from its building blocks when, at some stage some notable transformation in the system behavior emerges. This is spectacularly illustrated in the case of cellular automata ([14]), when a sufficiently complex rule of transformation is found to lead to the property of self-reproduction.

Finally, there is a very definite sense of emergence when one talks of the transition from the classical theory to the quantum mechanical theory, from Newtonian mechanics to the one based on the special theory of relativity, from the special to the general theory, or from the quantum theory to quantum field theory. In all these cases, a transformation of a theoretical scheme signals a distinctly new way of describing and explaining natural phenomenon as some parameter in the theory is properly taken into account without being dismissed out of hand (the Planck constant, the typical particle velocity in relation to the velocity of light, the strength of the gravitational field in relation to other forces in the theory, the rest masses of particles in relation to their energies).

In other words, there are numerous sources leading to *emergent properties* in complex systems, and emergence constitutes a powerful heuristic for the understanding of such systems across disciplines.

Still, the idea of emergence brings up philosophical and theoretical questions of a more fundamental nature. As promised, these will be referred to in the course of the next part of the present essay.

Complexity and reality: a close look at scientific realism

Reality and our interpretation of it

The very first thing I want to start from is that ‘reality’ is something that may appear to be self-evident, but that there is a catch to it – appearances are treacherous.

The foundational position that I adopt may be briefly stated in simple terms as follows:

> Reality exists independently of our mind – we ourselves are part of that reality – but all that we know and think of reality is a matter of our *interpretation*. In other words, we have to clearly demarcate between ‘reality itself’ and *our conception of reality*.

> Signals of various descriptions are incessantly generated from all the innumerable parts of reality, some of which impinge on our senses. These include signals generated *internally* – ones activating mental processes of diverse descriptions – reality is presented to us in the form of an external and an internal world made up of *phenomena.* The signals are processed by our mind and form mental impressions and then our *interpretation* of our external and internal worlds – the mental processes themselves are part of the infinitely complex dynamics of reality at large. The interpretation is based on *concepts, beliefs, and inferences*, and is *all that we have* by way of our conception and knowledge of the world.
>
> All the while, 'reality itself' continues to exist beyond our conceptual world – ever instrumental in constructing and reconstructing that world and ever deceiving us into believing that our interpretations constitute a *true* representation of itself.
>
> Our mental conception of reality is not apart from and secluded from reality at large – reality and our interpretation of it are *implicitly* correlated and form a tangled whole. Nonetheless, the fundamental fact remains that reality exists by and of itself and is self-determined, and that our mental world exists as a phenomenon within it while, *at the same time*, that phenomenon constitutes our sole takeaway from reality – we *sense* reality, we form our concepts and theories relating to parts of reality, but can never know how faithfully those concepts represent 'reality-in-itself'.

This, of course, is no product of my own fertile thought – there exists a long line of contributions from philosophers and scientists from antiquity to the present day, that cohere to form a certain position in the philosophy of science and, at the same time, help us in comprehending, explaining, and illuminating it – it is this position that I have tried to summarize above within my own limited means.

> In speaking of philosophers and scientists, I do not mean to exclude the insights and ideas – often of remarkable value – offered us by authors, poets, artists, sculptors, musicians, and very many others from various walks of life. The point is that the authors, poets, and all the others *don't take it upon themselves* to explain the world around us and to fathom out our relation to that world. Scientists are supposed to explore and infer the mechanisms underlying the workings of nature, while philosophers engage with foundational issues relating to existence, reality, and knowledge. Any individual entering into such an engagement may be said to be taking on the garb of a philosopher, at least for a limited time and purpose.

At the same time, it must be mentioned in no uncertain terms, that alternative views of the world and of its relation to our mind exist and *there is no ultimate guarantee* of the *truth* of any of these alternative views (including the one I propose to adopt) – at the end of the day, all these remain nothing more than *points of view*.

> The point of view I adopt in this essay is similar in many respects to the one explained in greater details in [1]. I may also refer to [18], where I start from the same basic position as Baggott's, and then set off in a different direction, exploring the cognitive roots of how science inquires into Nature, focusing on how inductive inference is enacted in the human mind and how hypothesis formation and (scientific) creativity may be realized in the mind of an individual. I also suggest [2], [3] as delightful and instructive readings that help in understanding the setting in which the present essay is put together. Later in the essay I will point out a few areas in which my take on our changing conception of the world differs from what I perceive to be Baggott's – but, once again, it is no big deal that one point of view may differ from another.

Even a child will agree that reality cannot be the same as its representation in our conception. But it is important to understand how this conception is formed and what knowledge it imparts of the world out there.

This is the concern of *scientific realism*, which inquires as to which items of our conception 'exist' out there and how our conception of reality *corresponds* to reality itself. In other words, scientific realism examines critically the nature of our interpretation of the world. And, it is precisely here that *complexity* enters in a big way.

Nature is one huge complex system – it includes *all* the complexity there is. This is so self-evident a statement that one often takes it for granted – philosophy tends not to give explicit recognition to lessons learned from the *science* of complexity. In the rest of this essay I will first jot down a few basic things that the point of view of scientific realism tells us and will then indicate, within my limited means, the directions in which one can hope to improve upon one's way of looking at reality by reckoning with the complexity of Nature – the *ultimate* in complexity, that is.

Observations on the viewpoint of scientific realism

This section is not meant to be an attempt at an exposition of the viewpoint of scientific realism but will include reference to a few areas where one finds continuing controversy within its fold.

1. Philosophy, of course, is a discipline that thrives in controversy, and scientific realism is no exception in this. Still, within the camp of scientific realism, there are a number of questions that philosophers seem to be worrying about with somewhat more than average concern.
2. Generally speaking, scientific realism concerns itself with how science views nature and what the *method* of science is supposed to be. In the words of Baggott:

   > ”In fact, almost a century of intellectual endeavour and argumentation appears to have led the philosophers further and further away from a consensus on science and the scientific method.” [1]

Among these worrisome issues is the one of the existence, i.e., the ontological reality, of ‘unobserved entities’ and the related one of the ontological reality of attributes of objects including ones that form part of the *theory* about these objects. Related to this is the question as to whether our theories are expressions of principles intrinsic to nature or whether, in contrast, they are *constructs* designed to describe and explain nature as captured in our conceptual world. And finally, there is the issue that poses the question as to whether successive versions of our theories represent progressively accurate descriptions of the mechanisms inherent in nature. All this needs a bit of explanation.

But even before we engage with the above worrisome issues, I will briefly comment on the apparently conflicting viewpoints of scientific realism and anti-realism.

Scientific realism and anti-realism

Scientific realism and anti-realism appear to be facing each other on the above issues across an unbridgeable gap. The gap appears to be even more unbridgeable in respect of the supposedly foundational issue relating to the very existence of reality outside and beyond our senses. As for me, I have already indicated in no uncertain terms that I do accept the viewpoint that there is a reality that is self-determined and is independent of our conceptions and theories. But, at the same time, I have also clearly stated that such an acceptance is no more than a point of view – the point of view that is associated with scientific realism. The seemingly opposite viewpoint that the existence of something called reality is a conceptual construct, is branded as anti-realism.

1. Differing viewpoints emerge in our attempt at answering questions that relate to an underlying *complexity*. Complexity is something that is inherently beyond the practical possibility of a *complete* description or explanation. And life does not allow us infinite time or leisure to settle such complex issues. In order to arrive at answers within our limited means and resources we adopt certain simplifying assumptions – all in the nature of beliefs induced from our prior experience. This is how all theories are built up and *meta*-theories are adopted – the latter being precisely what we call points of view. From a broadly general perspective, theories and meta-theories are all like beliefs generated in our mind. Among the web of beliefs, some are easily revised when weighed against evidence, but some are in the nature of durable beliefs that come to be formulated in such a manner as not to be in direct confrontation with evidence.

   For instance, I may entertain the belief that 'very few people are honest' as against the belief of my friend's to the effect that 'most people of this world are honest'. It is entirely likely that we will pass through life with both our beliefs intact, without ever being troubled with contrary evidence. What is more, despite the beliefs being seemingly incompatible, we may spend our life being the best of friends.

   In reality, no person is ever fully honest or fully dishonest. Honest and dishonesty are two descriptions that we use as tags attached to persons so that we can assess their behavior with relative ease without being burdened by too much of confusing intricacies.

2. The statement that a system is self-determined means that there is no external system or agency that determines its behavior. This, however, does not mean that the behavior is *determinable* or predictable through observations and inferences. Scientific realism makes an assumption that reality is self-determined, but does not bear responsibility of stating that the reality as a whole is determinable.

The opposition between apparently contrary points of view is never in the nature of an ultimate and indissoluble divide. There is always an extended middle ground between the two opposites, which bears testimony to the fact that the said opposites do not exhaustively divide the terrain one is looking at. It is often our shortness of vision that we do not see this and, having once formed a point of view, to which a contrary view is found to be posed, we become possessive of it (the other point of view similarly attracts its own takers) and we then come to be cursed with a *dichotomous* approach.

When scientific realism adopts the position that reality exists independently of our conception of it, that position is in fact one arrived at by way of a *meta*-induction. And when it further states that *all* our knowledge and belief about the reality is a matter of our interpretation since reality forever lies beyond our senses while being the perennial source of our interpretations, it is actually adopting a certain position in the context of a *deep and complex problem* that we face in describing our relation to reality. To someone not versed in the nuances of philosophy, the opposing point of view that reality is something that lies in our concepts, does not sound too different. This is not to say that the two points of view are not distinct from one another but only to state that the distinction is not a matter of hard evidence. Confronted with such seemingly incompatible points of view, one might as well adopt the broader one based on the Hegelian-Marxian dictum of the indissoluble 'unity of opposites' (something like the belief that 'people appear to be honest or dishonest depending on circumstances') but that, again, would be no more and no less than still another point of view.

Two other areas of discourse where scientific realism and anti-realism appear to be in conflict are, *first* the ontological status of 'unobservable entities' and their properties, especially ones that emerge in the context of the relevant *theories*, and *next*, the status of successivey revised *versions* of theory in various areas of science – whether or not they approach progressively to *truth* about Nature (see [22] for background).

Unobservable entities and theoretical properties

Broadly speaking, an 'unobservable entity' means one whose existence is inferred on the basis of indirect evidence, generally in theoretical terms. A commonly cited example in this context is the electron – an entity that cannot be observed with the unaided eye or even a microscope but one whose existence is still ascertained by numerous indirect means. Scientific realism accepts that the electron exists and that its ontological status is no different from other more mundanely experienced objects. It is to be noted, however, that the lack of directness in the observation of an electron means that there is an associated intrusion of theoretical concepts in what we refer to as an 'observation of an electron'. For instance, take the case of a *positron* – the *anti-particle* of an electron. The observation of a positron is yet more problematic as compared to an electron since it requires a certain minimum of energy to be generated and does not last long in material environment, and its existence, ascertained in specially designed experimental conditions, is yet more a matter of theoretical interpretation – indeed, the positron was first predicted on theoretical grounds in the context of relativistic quantum mechanics.

This raises the issue of how we interpret *theory*. As we see, the apparently simple question relating to the existence (or the *reality*) of an entity is bound up with the deeper question of the status of theories in relation to reality. Before dealing with this issue of what a theory signifies, let us focus on the apparently simpler issue of the *properties* of an entity such as those of an electron.

When we speak of an electron, it seems that we speak of it without reference to other entities in nature. The identity of an electron is established in terms of its charge and rest mass, in addition to its *spin*, the last named being a quantum mechanical property of the electron. While it seems that this identity is established without regard to other entities in nature, in reality it is not so and, moreover, it does not provide us with a complete understanding of what an electron 'really' is.

The assertion of the mere existence of an entity constitutes a metaphysical statement unless we also specify how that entity is related to the rest of the world – how it behaves in the company of other entities of nature. The mass, charge, and spin of the electron tell us a lot about how and where the electron is located within the infinitely complex web of inter-relations between the entities of nature but these still do not give us a reasonably complete information of how the electron behaves in this complex world of ours. Such information comes only at the cost of theory. For instance, the charge of an electron assumes relevance only in the context of the theoretical statement that the force between an electron and another charged particle conforms to the inverse square law named after Coulomb. While the Coulomb law describes the force between a pair of static charges, one can complement this with the force on a moving electron in a magnetic field so as to make up the expression for the composite *Lotentz force*. If the spin of the electron is also brought into the picture and one finally adds the gravitational force on the electron exerted due to other massive particles around it (commonly, however, the gravitational force turns out to be of negligible magnitude), one gets a reasonably complete description of how an electron is expected to behave in the company of other entities in the world. However – and this is of great relevance – such extended description is *still* inadequate for many purposes since it does not include the so-called weak interactions of the electron encountered in nuclear and sub-nuclear events.

All this goes to show that the mere existence of an electron is vacuous in so far as our understanding of the universe is concerned, and the fact of existence assumes significance as it gets concretely manifested through its behavior in the world made up of other entities. And we find that this is already a matter of quite extensive *theory*. Though the electron is uniquely identified in terms of its rest mass, charge, and magnetic moment, that identification is hollow unless looked at in the context of an appropriate theory which gives meaning to the rest mass, charge, and the magnetic moment. What is apparent is that the theory is context-dependent, i.e., needs to be continuously upgraded as the electron is observed in circumstances more and more remote from the world of our direct experience.

Theory as code

The really significant issue in respect of of our knowledge of a particle such as the electron comes up when one considers it to be moving in the field created by other particles that themselves move under mutual interactions, since it is only then that the relevance of the *equations of motion* of a system of particles appears in its true light. This is made clearer by referring not to particles with electrical and magnetic properties but to ones having gravitational interaction alone since the principles involved are understood then in simpler terms.

> I do not refer here to the space-time dependence of the gravitational field in interaction with massive bodies or to the issue of its integration in a unified theory of a broader scope. We will come to the question of the emergence of successively revised structures of theories later in this essay.

Considering a hypothetical situation where a number of massive particles interact among themselves in accordance with Newton's law of gravitation, one writes down the set of *equations of motion* of the particles, which is then supposed to capture *all the theory* pertaining to the system in question.

There arise two questions that demand our attention at this stage. The first of these pertains to the set of particles along with the equations of motion as constituting a *model*. And the second relates to the issue of the theory describing this model being in the nature of a *code*. The former question will be addressed in a later section in this essay (the idea of a model was briefly referred to in the introductory section), while the latter is of fundamental relevance now.

Does the set of equations of motion based on Newton's law of gravitation *describe* everything that can possibly happen to the set of particles in the model? Evidently not, since theory is no detailed description of reality (the experienced reality, that is, within the restricted context of the model). If a theory is expected to provide a complete and detailed description of experienced reality then it misses its purpose. In fact, a theory is the essence distilled from reality and its usefulness lies in its ability to produce a description when appropriately *unpacked*. In the present context, the unpacking is done by *solving* the equations of motion based on an appropriately chosen set of initial conditions. The solution constitutes a part of theory too but one that pertains to the mathematics of differential equations and is not an integral part of the theory pertaining to the model in question.

> The initial conditions (and the boundary conditions in the case of a set of partial differential equations) involve items of information *external* to the system considered in a model – information whose relevance arises from the fact that a model is something abstracted away from the rest of reality.

Another way of expressing what a theory signifies is to say that it acts as a *code* – and, the unpacking referred to above is analogous to the process of *decoding*, with a key provided by the mathematical theory of solving a given set of differential equations. The code, evidently, is not the same thing as the *result* obtained in the process of decoding, which is the actual stuff for which the code was designed in the first place. What that result would be for a given set of initial conditions can be known only *after* the decoding is done. And, that result may contain huge surprises, vanishing without trace however hard one looks at the code alone. Imagine a computer program written so as to obtain the answer to an intricate problem, that answer being known only when the program is actually run on a computer, with the necessary data fed to it, and that answer actually adds to our knowledge while the program in itself does not. The famous ‘four-color problem’ was solved with the aid of computer programs, and its solution (and not the programs) constituted mathematical knowledge on a question over which mathematicians had struggled for a long time.

> Other analogies where the action of a set of rules operating on a basic package, in conjunction with additional information fed by hand, leads to the unfolding of diverse consequences that add

> to our knowledge of the relevant models include (a) the generation of the multitude of theorems of geometry from the basic axioms by the action of a set of rules of deduction, (b) the operation of rules of sentence formation on a set of core principles of a grammar, generating an entire language when employed in the context of a basic set of words (c) the solution to the Schrödinger equation (the code) in the context of an appropriate Hamiltonian leading to the spectral characteristics of a molecule.

In summary, a theory pertaining to a model acts somewhat like a code in respect of the detailed behavior of that model when appropriate rules of decoding are employed in conjunction with appropriate information setting the context of the decoding process. *Knowledge* of how the model is expected to behave under various situations is obtained only when the decoding is actually performed, and cannot be meaningfully said to have been 'already there' within the code.

What is more, when looked at in the context of explaining and predicting the behavior of the system (some part of the universe) represented by a model, the 'code' (i.e., the theory) itself is generated from experience by a process of abduction, and gets revised from time to time in a process that is said to be a major feature of science. We set aside this process of continual revision of theory for the time being, and consider how the code *leads to* but cannot be said to *contain within itself* all the knowledge about nature that we can arrive at, including all the novelty that we can predict.

> This is the big difference between a theory and a code that one has to keep in mind. A code is written by someone who knows how it operates, but a theory is not like that, unless we adhere to the view that it is our guess at a code 'written by God'. God or not, a theory is just a clever guess at how various parts of Nature behave; it is our abstraction from observed reality and is supposed to be our guide to unknown terrain in our journey through the maze of reality. What the theory tells us on being unpacked is not known beforehand because we are no God who is supposed to have written the entire code of Nature. On being unpacked the theory may be found to be junk or else, may provide us with knowledge of how various parts of nature behave. In this essay, I outline the view that our ceaseless attempts at revising our theories does *not* constitute a process of arriving at some ultimate code hidden within the folds of Nature. As I have repeatedly mentioned, this is just a point of view, nothing more.

In order to illustrate this we return to the consideration of the equations of motion (based on Newton's law of gravitation) of a system of particles. When solved with data corresponding to initial conditions for a system of two particles, these equations describe a regular behavior of elliptic motion of the particles around their common center of mass. However, when one tries to solve the equations for *three or more* particles one observes a multitude of behavior patterns of the model including regular motions along with irregular or *chaotic* ones. In other words, the theory (comprising of a set of equations of motion – the 'code' in the present context) pertaining to a number of particles interacting by Newton's law of gravitation does not in itself constitute a description and explanation of the behavior of the particles, and the question that now assumes relevance concerns the way such description and explanation is arrived at. As we have pointed out earlier, the process of arriving at the description and explanation is more often than not at least *as complex as* constructing the theory itself. As a point of interest, one can, if one wishes, refer to Newton's law of gravitation as the *theory of everything* in so far as systems of gravitating particles are concerned, but that does not, in itself, have as much of relevance as one could wish for in providing us with knowledge about behavior of such systems.

> This is because we would not know, before the consequences of the equations of motion are worked out for all possible contexts (i.e., all possible numbers of particles and all possible initial conditions) and actually compared with phenomena in nature – not only the ones that we now experience, but ones that will be played out at all time to come everywhere within the infinite expanse of nature. Who knows, there may be surprise hidden somewhere –indeed, the lessons from the theory of complexity tells us that there *will* be surprise, perhaps when we least expect it (the fat-tailed distribution at work!) – and we will have to guess at a revised theory. We do not know beforehand what our theory is going to uncover.

Before I proceed further, I will include here a brief summary of the topics touched upon up to this point in the present section.

Nature generates all our conceptions pertaining to what it is and how it works, but those conceptions do not capture Nature as it is – the question of how nature conceived by us corresponds to nature-in-itself is a deep and complex one. Indeed, it does not carry much sense in talking of 'nature-in-itself', not as much because the latter is transcendental – it is *a priori* and independent of our senses, though – as because it is the ultimate in complexity.

The mere *existence* of entities in nature is devoid of meaning and relevance unless we also talk of their *properties* and the way they behave in the world. And, properties are not inherent in those entities independently of their mutual interactions. Even assuming that an electron is uniquely identified by its charge, mass, and spin, its behavior is known only when the Lorentz force law governing its motion in the presence of other particles is specified, in addition to the universal law of gravitation – we do not consider, for the moment, further revisions in the theory of particles and their interactions.

This means that not only is the question of the mere existence of entities devoid of content, that of their properties too is meaningful *only* with reference to appropriate *theory* – the issue of the existence of unobservable entities (indeed, of *all* entities) is essentially and inseparably tied up with the theory describing their behavior. Theories governing the behavior of entities constitute an important component of *our interpretation of nature*. Statements about the existence of entities are meaningful only to the extent that theories explain our observations on them, though customarily the question of existence is seen as one separated from that of theories.

Theories, however, are much like codes that are to be unpacked appropriately to actually lead us to knowledge of how the entities making up the world behave and evolve in it – theories are meant to *explain* why the entities (or systems of entities) behave the way they do and to *predict* how they (the systems, that is) are expected to evolve.

The question of ontology

While the assumption – I have called it a point of view – of a mind-independent nature (the ‘reality’) – is said to distinguish scientific realism from anti-realism, the ontological assertion of existence becomes meaningful only when it is complemented with the ontological significance of the *properties* of entities that exist and, as we have seen, then, of *theories* from which we can derive the behavior of entities and systems (of those entities).

However, it seems too far-fetched to talk of theories being ‘real’ in any sense. Various points of view within the fold of scientific realism do not unequivocally assert the ontological reality of theories, mostly because theories are endowed with a *fluidity* – they come and go, and do not *reside* in the entities of the world. This is a view that makes a clear separation between the existence of entities and the theories that explain and describe their behavior – however, this needs to be examined closely if scientific realism is to come clean on consistency.

When we talk of an electron – an electron describing a circular arc in a magnetic field and ionizing a gas it moves through – we are actually making statements within our experience of reality and our interpretation of it. It is important to recognize that these statements only *correspond* to things and their behavior ‘out there’, the interpretation being made possible by means of signals sent out from these components of reality to our senses and our instruments. However, the exact nature of this correspondence remains fundamentally undefined.

Among these statements regarding the behavior of entities, the *existence* part is implicitly (and almost universally) distinguished from the *theory* part (Lorentz force, ionization potential, and all that). It does not seem problematic to state that the electron spoken of in our interpretation *truly* corresponds to the electron residing ‘in reality’. When it comes to theory, however, the correspondence is taken to be true but only *approximately* (whatever that may mean) – there appear revisions from time to time in the theory, supposed to be taking us progressively closer to the ‘actual’ behavior of electrons ‘out there’.

> Indeed, the very notion of an entity is deeply theory-dependent, though we commonly gloss over this aspect in philosophical discussions: the 'electron' featuring in the quantum theory of atomic spectra is certainly not the same entity as the 'electron' on the standard model.

From the ontological point of view, theories are taken to correspond to objectively existing 'laws of nature' – ones that are supposed to determine the behavior of entities. And, what is more, all these laws of nature (Newton's law, law of gravitation, Maxwell's theory, and so on) are commonly assumed to be *embedded* in an all-embracing 'unified' theory, also inherent in nature, which all our theories progressively lead us to.

The point of view – to be further explained below – adopted in the present essay differs from the one expressed in the last paragraph. It posits that theories are constructs put together in our interpretation of reality (see sections Ontology of reality: entities and correlations and Do theories correspond to 'laws of nature'? for further elaboration) and have no counterpart inherent in nature – they are contextual and undergo *non-monotonic* revisions. What remains objective is the behavior of entities that they predict – the behavior we experience in our phenomenal world, since theories are constructed precisely to explain this behavior of systems at various levels of complexity. It is the behavior of entities that gives them identity – an identity that is once again contextual, being the phenomenal aspect of some tiny part of the real world out there. One may think of entities along with their behavior – the two can be separated only notionally – as a 'projection' onto the context set by our senses and our instruments of observation, along with our prior beliefs and theories emerging in our interpretation of the world.

It all appears to be confusing stuff, but confusion is avoided only at the cost of inconsistency.

Complexity and incomplete descriptions

Complexity throws new light on all the discourse about *correspondence* between *the* reality out there and our interpretation of it.

It is precisely because of the all-pervading complexity of nature that *whatever* we say or think about it *has to be partial and incomplete*. And, it is precisely because of this too that *no* statement of ours ever *truly* corresponds to the reality out there. There is no question even of an approximate correspondence since theories change dramatically as the context of a model (to which a theory applies) is changed.

> As I said earlier, the distinction between our conceptions and the reality out there is not difficult to recognize and accept. What is more difficult, however, is to see why they need not correspond exactly and truly to each other, subject to inessential corrections from time to time. It is here that complexity assumes command over everything and overrides all other philosophical considerations.

The fact that it is essentially metaphysical to talk about reality outside of and beyond our interpretations, does not owe its origin to any transcendence or any similarly deep mystery that lies beyond our comprehension – it is due to the *pervasive complexity* of nature. This is something that we infer from our conceptions of parts of nature that we are confronted with in the course of our everyday experience and our scientific explorations. Consider, for instance, a gas made up of an enormous number of molecules. It is only a tiny part of nature, and is not even a highly complex system if one assumes that the molecules are all identical classical particles with fixed and identical two-body interactions between them. Even so, nobody can make meaningful statements about *all possible* types of behavior of the gas – everything we say about it is by the very nature of things a partial and incomplete statement – one where some aspect of its behavior is abstracted out from the rest. The idea of the gas considered in isolation from the rest of the universe is itself an idealization and constitutes a *model*. Even when some kind of interaction with external systems is considered, say, with a specified field or with a heat reservoir, one is still left with a model – an extended one to be sure, but a model nevertheless.

All our experience, all our scientific explorations, always occur within some limited *context* set by the range of objects whose interactions are relevant in respect of the experience, the limitations of our senses and our scientific instruments, and of our current state of personal and inter-subjective beliefs and concepts. All these together interact in the setting up of a *model* – an abstraction from the complexity of nature – complexity to which no limits have ever been found to apply. Nature, in other words, is *infinitely complex* – with an effectively infinite number of *dimensions* to it, i.e., an effectively infinite number of independent aspects relevant for a supposedly complete description pertaining to it.

In other words, *everything* that we consider relates to some model or other – whether or not that model is precisely defined. Models in physics and chemistry are mostly defined with great precision, where the role of our vaguely defined beliefs and concepts is done away with in terms of a number of precise mathematical assumptions and mathematical rules of derivation. Even so, the theory applying to such a model does not always lead to precise and definitive conclusions because of mathematical difficulties involved, and one needs schemes of *approximation* in respect of the models. These approximations are symptomatic of the complexity of the model in relation to known rules of mathematical derivation. One can go further and say that no theory, approximate or otherwise, ever applies to reality at large which is infinitely complex and cannot be experienced or explored *as a whole* either by means of our senses or by means of scientific instruments.

Thus, any and every theory applies to some part or other of nature at large as reflected in our experience, sought to be described in some context that may or may not be precisely defined. If one focuses on some part of our experience without specifying the context even by implication or even vaguely, then the model itself becomes undefined.

On the other hand, it might appear that one and the same system can be the subject of different models under various different contexts. For instance, a gas made up of an enormously large number (say, N) of molecules, all confined to move within a specified volume (say, V) may be looked at either in isolation from all other systems around it or in interaction with a large heat reservoir that can exchange energy with the gas, where particle exchange between the two systems (the heat reservoir and the gas under consideration) is not allowed. In the latter case, the energy of the gas can fluctuate along with fluctuations in the energy of the reservoir, covering a range of the microscopic states of the latter. One can, however, *average* over all these fluctuations over the microscopic states of the reservoir and focus upon the states of the gas alone and set up the model in such a way that this constitutes a model of the gas (without overt reference to the reservoir) for specified values of V, N and the *temperature* T, as compared with the other model for the *isolated* gas where , along with V and N, its *energy* gets fixed at some specified value (say, E).

> We have to keep reminding ourselves from time to time that, when we speak of a model as an abstraction describing some part of nature, we actually mean some part of our phenomenal experience of nature.

Can one then, in all fairness, say that the two models refer to the *same* gas? This apparently simple question to which everyone will answer yes, takes us back to the question as to whether and to what extent a 'system' or an entity can be abstracted away from its behavior resulting from its interactions with systems around it. It is only in rare situations that one can talk of a system all by itself, as in the case of the isolated gas. The complexity of the world implies that even very weak interactions with the rest of the world can lead to essential modifications in behavior. In other words, various models of what appears to be the same system are to be considered as essentially distinct from one another since they correspond to distinct contexts in which its interactions enter into the definition of these models. Here the term 'interaction' is meant to refer to both the interactions between the subsystems and those with the surrounding systems.

Significantly, *the theory pertaining to a model depends to a remarkable degree on the context defining it.* This question will engage our attention to a marked degree later in the present essay.

Ontology of reality: entities and correlations

The ontology of reality pertains to the issue of what resides ‘out there’. Truly speaking it falls within the domain of metaphysics to speak of entities or qualities that constitute ontological reality. Nonetheless, it can and does fall within the scope of our world-view – our philosophical point of view or, in a manner of speaking, our mindset – that forms the backdrop of the more substantive statements that we make in science and philosophy. Though a point of view cannot be either proved or disproved, it does influence the *mode* in which we inquire into the workings of nature

> An illustrative analogy: I may have the mindset that few people in this world are honest, while my friend working with me in our project lab may have the one that most people are honest. Evidently, this differing viewpoint will influence the evaluation of and working relation with a new entrant to our lab that each of us will develop.

Thus, when we speak of an electron as it exists in reality, we actually speak of something else – an electron as it exists in our interpretation of nature in some context. As we have indicated in earlier paragraphs, this distinction between entities in the *noumenal* and *phenomenal* worlds is devoid of meaning when applied to an entity (such as an electron) *abstracted away from its properties* – its behavior vis-a-vis other entities in this world. What is more, the behavior of entities cannot, in a similar vein, be abstracted away from *theories* abut these. Theories are mental constructs meant to provide us with explanations and predictions, and hence belong to the phenomenal world of our interpretation. The question that scientific realism now faces is the following: to what, if anything, in the noumenal world do the theories correspond?

As we have seen, scientific realism is inclined to posit an unambiguous correspondence between phenomenal and noumenal entities. So, according to the same trend of thought, there has to be an unambiguous correspondence between a theory and the associated noumenal posit – an intrinsic *law of nature*. Just as phenomenal entities acquire meaning only in relation to appropriate theories, similarly, it is only ‘natural’ that the corresponding noumenal entities acquire ‘meaning’ within the fold of laws of nature. Let us, for the time being, ignore the fact that it is *meaningless* to talk of ‘meaning’ in the noumenal world unless we allow ourselves to tread dangerously close to the assumption of a Creator.

> *I*, for one, don’t have an issue with a viewpoint that looks up to His powers, but scientific realism seems to have; this makes me want to examine closely the posits of scientific realism as I do in this essay, since I should, at the end of the day, like to call myself a realist – nonetheless, I certainly don’t have an issue with other points of view such as anti-realism and social constructivism. I can only clarify what my viewpoint is – there is no intent whatever to prove its *correctness*, if only because that is an impossible task anyway.

In the course of all our experience in the world, what we find in the behavior of entities is their all-pervading mutual *correlations*. More precisely, the world of our experience is made up of an infinite multitude of *events*, where an event refers to an entity (a ‘particle’ in a description arrived at by abstraction) marked with *space and time* co-ordinates. Theories are constructed out of all the multitudes of correlations between events by a process of abduction – as I said, theories are the distilled essence of our experience.

What corresponds to the phenomenal correlations are, once again, correlations in the noumenal world – correlations existing ‘out there’. In other words, the ontological reality of entities acquires meaning only in association with the correlations among events existing in reality, outside our conceptual world, independent of all our conceptions and beliefs. Once again, this is an assertion without proof, but this, at the end of the day, constitutes the point of view of scientific realism.

While this completes the story as far as I am concerned, the question remains as to what our *theories* correspond to. This question arises when we extrapolate from the original posit that events in the noumenal world unambiguously correspond to phenomenal events. This seems to raise the expectation that *something* has to exist so as to unambiguously correspond to the *theories* too.

But theories are nothing but the distilled essence of our experience, obtained as *constructs* in our conceptual world resulting from the interpretation of our experience, and scientific realism has absolutely no responsibility to seek out correspondence regarding everything that exists in our conceptual world. For instance, it is absolutely not a fact that all our beliefs and concepts have a correspondence with something out there. And, theories are nothing but glorified beliefs about nature that apply to *models*. Of course, theories are beliefs of a very special kind – ones that have to bear the responsibility of producing results that must have a close correspondence with some part of our experience. Even so, they have no responsibility whatsoever to have a correspondence with something existing out there independently of our conceptions.

At this point, I'll sum up this part of our discussion.

> Our experiences in life are generated by multitudes of signals perceived by our senses, aided by scientific instruments, that give rise to impressions and concepts in our mind. As such, they must undeniably correspond to real events happening 'out there', in the noumenal world that lies beyond all our conceptions and interpretations constituting our phenomenal world. This correspondence is fundamentally made up of two parts – a correspondence between events in the two worlds, and one between *correlations* between events. Having said this, however, I must hasten to add that events and their correlations form one indissoluble whole – splitting the two must lead to philosophical pitfalls.
>
> The task of *theories* is to generate conclusions *within the context of models* that fit with experience. A model is a cleverly constituted object that abstracts from actually existing events in our phenomenal world so that the conclusions of a theory applying to it agree closely to actual experience.
>
> A theory is like a belief formed in our mind and does not have to correspond to anything in the noumenal world, though the conclusions generated from it have to have a close agreement with our experiences and hence, with events

> and their correlations in that world.

It is the notion that theories have to correspond to what are referred to as 'laws of nature' that lead to questions and paradoxes. In particular, there arises the question as to whether our theories, by means of successive revisions, approach more and more closely to mechanisms inherent in nature that explain and predict the behavior of reality as a whole. The notion of *incommensurability* of successive versions of a theory is at odds with this commonly entertained idea of approach to the ultimate *truth* inherent in nature. We will come to this later in the present essay. For now, we focus on a number of issues that will finally lead us to an appraisal of this idea of correspondence of theories with intrinsic mechanisms of nature and then to the one of *one single* grand theory describing the fundamental law of reality at large.

Further elaboration of the the concept of incommensurability of theories and of how it fits in with the viewpoint of scientific realism will be found in the final section, Summing up: complexity in reality.

Models and their significance

Experience with complex systems we encounter in the real world tells us that these are generally characterized by the feature of *co-evolution* where *everything* pertaining to a system evolves with time, including the constituent entities and the nature of their mutual interactions. The interactions can only notionally be separated from the entities themselves – being represented by links and nodes in the network representation of a complex system – and it is their co-evolution that is fundamentally responsible for the behavior of the system itself.

> Recall that it is more appropriate to refer to *events* rather than to entities – events are entities marked with appropriately chosen *space and time* co-ordinates. There is a subjective or observer-dependent aspect to space and time co-ordinates, though the entire multitude of co-ordinate systems corresponding to different possible observers are related to one another in an objective

> way – one that determines the *structure* of space-time. The structure of space-time is part of the theoretical framework of physics, and is objective in the sense that it is independent of the mode of description adopted by this or that specific observer. The *concept* of space and time (or, briefly, space-time) applies to our phenomenal world and refer to the noumenal world only partially and incompletely. More precisely, space-time has the same status as entities and events, in respect of which there is a partial and context-dependent correspondence between our experience and the noumenal reality.

A model is an abstraction where one or more aspects of the co-evolution may be ignored for the sake of simplicity of analysis. The fact that the model can be useful *in spite* of such simplification needs separate attention on our part. Recall that a complex system, in its time evolution, generally involves a number of distinct *scales* in space and time, where the term 'space' need not mean the three dimensional physical space but a phase space that can have an arbitrarily large number of dimensions. The existence of such scales is generally a manifestation of a spectrum of interactions between the components of such a system. Such multiple scales characterizing the behavior of the system results in co-existing nested regimes of stability and instability where each such regime (in space and time) can, in an approximate sense, be described in terms of simpler, *reduced* systems.

As a simple instance, we refer back to the gas (with specified values of V, N) isolated from its surrounding systems with some specified energy (E). Observed on a *large time scale*, the gas attains a state of stable equilibrium when its properties can be modeled in relatively simple terms, though even such a simple model may involve formidable mathematical difficulties in yielding conclusions that can be compared with experimental observations. On the other hand, one can compare this model of an isolated sample of a gas with a model where the gas attains equilibrium while in contact with a large heat reservoir at some specified temperature T (which now replaces the energy E of the gas).

One may feel justified in saying that the two models referred to above describe the *same* system – a gas. Strictly speaking, however, the two models refer to differing contexts relating to the interactions of the gas with other systems around it where the interaction may result in exchanges of various types, including the exchange of chemical species. And, since it is meaningless in principle to talk of a system without reference to its interactions with other systems in the world, the two models are to be looked at as distinct ones, though in a practical (and loose) way of speaking, they may be said to involve the same system. Indeed, a model is made up of a certain set of system (molecules of a gas) with certain interactions characterizing these *without regard to* what happens elsewhere in the universe. Such models yield results in close agreement with what is observed in real systems, if the interactions ignored in the model are in fact of negligible consequence in the case of the relevant experimental situation. In the case of the gas in contact with the thermal reservoir, this is the situation if the interactions with the reservoir are sufficiently weak.

> In summary, complex systems are characterized by stable and unstable regimes in space and time, distributed over a range of scales, as a result of which one can have subsystems that can, in approximate terms, be represented by means of models – ones that lead to results in close agreement with observed behavior of the subsystems. Various different models can be constructed for any given system, where the latter interacts in various different manners with other systems within a bigger complex system. Though one can loosely say that all these different models pertain to the same system, they can imply very different behavior of the system because it is characterized in these models by interactions of different kinds.

As we see, it is in principle not quite right to speak of ‘a model of a system’ since, more pertinently, a model describes *a set-up* involving one or more systems along with their interactions with other systems, where the latter may be considered as *external* to the model. However, the interactions with these external systems have to be incorporated in precisely defined terms in order that the model may be useful.

Thus, simply stated, a model is a chunk scooped out from a bigger complex system, where all relevant interactions, both among internal systems and with external systems are appropriately specified. In the case of biological and social systems, or more generally for complex adapive systems (CAS) the interactions cannot be precisely specified, but one can specify in general terms how the states of a constituent of a complex system change under the influence of other constituents it interacts with. Interactions among systems lead to correlations that constitute the basis of the behavior of systems. Generally speaking, the behavior of a system obtained from a model, may depend markedly on the *context* in which the model is defined.

The statement that theories apply to models (and *not* to systems) and that the behavior of a system that is derived from the theory describing a model may depend markedly on the context – a simple enough statement on the face of it – has far-reaching philosophical consequences. To see this, we have to take into account one other important set of facts about theories and models that we will now have a look at.

To begin with, Models are useful only when they lead to behavior of systems in close agreement with the behavior observed under conditions that may be actually realized. For instance, the model of a gas in interaction with a large thermal reservoir where the interaction is of such a kind as to correspond to some specific value of the temperature T, very closely reproduces (under an appropriate set of additional conditions that we keep implied for the sake of simplicity) the behavior of an actual gas in a metal cylinder kept exposed to air in a room under stable atmospheric conditions.

Further, when one commonly states that a model describes the behavior of a system on the basis of a theory, it seems on the face of it that the theory is *known beforehand* and the behavior of the system under consideration *follows* from it. In reality, the theory underlying a model often results by a prolonged series abduction and inference based on observations on real-life situations, under proper laboratory control, as necessary. In other words, one has a complex and interwoven relation where theory is induced from experience and then that theory is applied to models so as to lead to behavior that closely reproduces the behavior observed in real-life situations.

In contrast to real-life situations where the complexity of the phenomenal world is often of non-trivial consequence, models are useful because they can be defined with precision, regardless of the complexities existing in the real world beyond the scope of their definition. In the case of the physical sciences, the definition of a model can be as precise as one likes, and the rigorous rules of mathematical derivation can be invoked to work out the consequences of the theory applying to the model, subject to the errors of mathematical approximation that are often found to be essential in such derivations (these statements apply only qualitatively to complex adaptive systems; see comments below). What is more, in the mathematically well-defined models, one can also work out the limits of error within which the results can vary so that, on comparing the consequences of the model with experimental observations, one can determine whether and to what extent the model deviates from reality in virtue of the abstractions and simplifications involved in setting it up. All this goes to make the models and the theories useful and essential in the physical sciences.

On the other hand, in geology, meteorology, biology, population genetics, epidemiology, economics, finance, administration, social studies, and similar other fields, one meets with progressively diminishing mathematical rigor, though the use of high-powered computers have brought all these fields within the fold of what can be loosely referred to as the scientific method, where the consequences of models can be worked out (to within limits) and compared with experience. Significantly, as we move along the above list of fields of study, the focus shifts progressively from CPS to CAS, and the variety and complexity of behavior increases.

In all such areas of study, the complexity of nature makes it imperative to make use of models and theories – induced from real-life observations by a process of abduction and inference – where appropriate rules of derivation are invoked so as to work out the consequences of the theories describing the interactions characterizing the models (among subsystems and with external systems as set by the context of a model), and to finally compare the findings with experience in real life, gained under controlled conditions wherever possible.

In summary, *theories are constructed in a process of abduction, inference, and abstraction, and are applied to models* – theories are nothing but constructs that are of vital necessity in making sense of the infinite complexity made up of entities and their correlations that we experience in our phenomenal world and, eventually, of the *real* world from which the phenomenal world derives in a process of conceptualization and interpretation.

The noumenal and the phenomenal

The terms 'noumenal' and 'phenomenal' have been taken from Kant, from whom the modern era of discourse on scientific realism can be said to have originated (see [11], esp., chapter 1, chapter 6). However, Kant's terms of reference regarding the two worlds were different as compared with those used in the current discourse on scientific realism and, moreover, numerous distinct points of view relating to the exploration of reality undertaken in our scientific enterprise continue to exist from days preceding Kant.

In contemporary terms, the noumenal world, which is the real world beyond the phenomenal one captured in our concepts, exists in and by itself, regardless of any kind of 'intellectual intuition' that transcends our 'sensible intuition' ([25]) – which is where the 'noumenal' referred to in the present essay differs from that in Kant's point of view.

> However, I intend not to harp on differences but to explore where different points of view interpenetrate so that there may result a deeper understanding of these, along with the possible emergence of broader points of view – more fruitful in making sense of our existence and our experience in this complex world of ours.

Within my own limitations in having a solid grasp of the current literature on scientific realism, I refer to the noumenal world as being made up of events (i.e., entities located in space-time) and their correlations that correspond to entities along with with their interactions in the phenomenal world captured in our interpretation of the noumenal world. As for the entities and their interactions in the phenomenal world, these are manifested (i.e., their *being* gets expressed in their *becoming*) only through their *properties*, where the latter correspond to correlations of diverse types in the noumenal world. In this sense, we speak of correlations in the phenomenal world as having their counterparts in the noumenal or the 'real' world.

The infinite multitude of correlations among events in the phenomenal world (and, correspondingly, in the noumenal world too) are sorted out in our conceptual world by means of *theories*. Theories, however, are constructs in our mind, constituting the distilled essence of our infinitely complex experience, and are meant to explain and predict the course of occurrence of events. Theories apply to models and capture partial truths about the phenomenal reality. They do not possess a counterpart in the real world, and do not correspond to purported laws of nature leading us to intrinsic mechanisms underlying the processes in the real or noumenal world. What are termed 'laws of nature' can only refer to the theories resulting from our interpretation of events experienced in the phenomenal world.

Here I include a few words on space, time, and the structure of space-time. Space and time (or, space-time in brief) are identifying indices ('co-ordinates', somewhat like book-keeping entries) that constitute an ordering among events in the phenomenal world, where we assume for the sake of convenience of reference that a similar ordering applies to corresponding events in the noumenal world as well. The space and time co-ordinates assigned to an event are observer-dependent, though the ordering itself, expressed in terms of the space and time co-ordinates that can vary from one observer to another, is observer-independent. The theoretical description applying to the phenomenal world posits a *structure* of space-time that is made explicit in the general theory of relativity where, once again, the structure is an objective concept, depending on the mass-energy distribution in space and time (the so-called 'stress-energy tensor') and determines a set of quantities depending on the gravitational field strength.

> The structure of space-time an objective thing in the sense that it can be treated on the same footing as events in our phenomenal world that correspond (in a sense that cannot be specified completely) to events in the noumenal world. However, the way this structure is accounted for in

the current theory of gravitation is model-dependent and contextual.

Does the theory of space-time and gravitation apply to a model or to our entire phenomenal universe? As with every theory, it does apply only to a model – one where all interactions and events on length scales smaller than the so-called *Planck length* and time intervals smaller than the *Planck time* are ignored. This actually sets the context in which the general relativistic theory of space-time and gravitation is defined since it allows one to deal with quantum mechanical effects and gravitational effects independently of each other.

As stated earlier, general relativity is nothing but a theory that forms part of our interpretation of nature and, strictly speaking, is not intrinsic to the ‘real world’. As a theory, it is no doubt a remarkable one that explains a vast range of natural phenomena but is still a distilled essence of our experience within this range – one where quantum mechanical effects have no influence on gravitation. Beyond this range, one needs a fundamental restructuring of the theory, where quantum field theory is to be integrated with the theory of gravitation.

To continue, we have spoken of entities and their correlations in the noumenal world. This is where we have implicitly taken a liberty in projecting our concepts arrived at by abstraction from the phenomenal world. It is an abstraction to separate entities or events from their correlations, manifested in the form of various properties of the former in the phenomenal world. Strictly speaking, we do not have hard evidence to make specific statements about the stuff the noumenal world is made up of. But points of view do not wait for hard evidence, and that of scientific realism asserts that the latter is made up of entities and events *corresponding* to the ones encountered in the phenomenal world. Indeed, our senses have evolved in such a way that some such correspondence holds because of the obvious adaptive value of it. However, the same adaptive process ensures that the entities and their interactions we sense are context-dependent. Thus, what we sense and observe with our bare eyes provides us with only a cross-section of the entities so observed (for instance, a tree leaf as a flat object of green color), while more demanding and specialized contexts reveal other particulars (the venation of a leaf, and its stomata when examined by a botanist). It then becomes impossible to speak of an entity 'as it really is'. Entities existing in the infinitely complex reality are complex systems themselves, and there is no final or ultimate description of such a complex system – only so much of the system is revealed in any given context.

> For instance, in a hypothetical situation corresponding to a more pervasive experience of nature on our part, the 'noumenal stuff' may even turn out to be a an infinitely extended field satisfying a nonlinear evolution equation. Even if one could write down a Hamiltonian density describing such a field, that would still not qualify as the ultimate theory of reality since a further expansion of our range of experience may demand a renewed attempt at a radical revision of the theory since, simply stated, the latter is nothing more than a construct.

Still, the noumenal reality is not something intangible and transcendental – it is a concrete thing, though infinitely complex. If we prevent ourselves from making any assumption whatsoever of this reality, we can speak only of the 'noumenal stuff'. But our points of view and our inferences arrived at inductively do not retreat timidly when called upon to make assumptions just because of lack of hard evidence – we constantly keep on making assumptions till some are proven wrong by evidence. Bold assumptions, consistent with whatever evidence we have, are things of thrill and are capable of making us more and more adaptive in our journey through life.

Scientific realism does not care much to be non-committal and to describe the real world as one made of just 'noumenal stuff'. When we have the perception of touching a table-top our senses give rise to some specific conception in the phenomenal reality, but this does not mean that we have had no contact with something tangible in the 'real' reality out there – we did indeed have such contact (as scientific realism is not afraid to tell us) when signals were sent out to our senses (to be processed in our mind), giving us the impression of the table-top in our phenomenal reality.

There is, however, a rider – one that it does not pay to ignore. While accepting that the noumenal reality is real enough and not just a cleverly made up concoction, it does not pay to be too confident to say that the conception of the table-top, based on the signals sent out to our sense, is *all there is to it*. Every conception, every interpretation, is incomplete and partial, having had its origin in some partial and contextual interaction of our senses (extended by the use of instruments) with parts of the noumenal reality – the latter is infinitely extended and an infinite-dimensional complex system, incessantly sending out an infinite multitude of signals of all kinds in all directions, to be captured again by parts and constituents of the same system, setting up correlations between all the innumerable parts of same the noumenal reality, while some of these signals are received by our senses which are themselves parts of the same reality. In other words, our conceptions are nothing but consequences of correlations between parts of the noumenal reality.

I repeat that all this is nothing but a point of view, an assumption that may be termed a meta-induction, one we adopt as a guide to our scientific quest – no more and no less.

Entities that are partially and contextually sensed by our interaction with parts of reality (the noumenal reality, that is) are not sensed in isolation from their properties – their interactions with other entities sensed in a similarly partial manner. Like the perceptions of the entities, the properties are also a matter of sensation and perception, i.e., in the ultimate analysis, of *interpretation* in our mind. Finally, the properties of entities are explained by *theories* that are likewise constructed in the mind by a process of abduction in which induction and deduction go hand in hand.

Do theories correspond to 'laws of nature'?

The statement that theories are constructs does not receive open-hearted approval from scientific realism, since the latter seeks to establish a correspondence between theories that reside in our minds and the purported 'laws of nature' residing in the real world lying beyond the mind.

> I disregard here the flaw inherent in the notional separation between the mind and the 'real world' – as if the mind is something distinct and apart from nature – and accept it as a way of simplifying our discourse. Even as the mind is actually a part of nature, it is a special entity

> capable of forming impressions of the rest of nature and even, to some extent at least, of itself.

The only things that are to be accepted as 'real' are entities and their correlations (or, more precisely, the indissoluble unity of the two) – *all* the rest are our interpretations aimed at making sense of the infinitely complex experience arising from these, where 'making sense' means a process of adaptation of our existence with the world of our experience.

To repeat, the correlations among the entities in the noumenal world create an impression, by means of multitudes of signals (these being, in the ultimate analysis, in the nature of correlations themselves), in our mind that we call experience. Theories are nothing but constructs in our attempt at sorting out the complex experiences and making use of these for the purpose of explanation and prediction.

The notional flaw that, at times, afflicts scientific realism consists of trying to project our theories on to the noumenal reality – to assume that *something* must reside out there that generate the theories in our mind just as entities and their interactions in the world of our experience are generated from the 'real' entities and their correlations by means of signals. That 'something' is referred to as a 'law of nature' specific to some domain of inquiry. However, in order that such a correspondence may exist between theories and the purported laws of nature, either of two things has to happen: *either* signals of some kind are to generate this correspondence, which is a possibility we discount as having had no evidence to rest upon unless such signals are of divine origin, *or* the laws of nature are to be generated by a process of abstraction *analogous* to the one in which theories are arrived at in our mind.

Looking at the second possibility, which is in the nature of an extension of the first, one has to assume that the 'laws of nature' are to be inherent in the noumenal reality, containing in them the distilled essence of all entities and their correlations, and that these 'laws' get impressed in our minds as theories by some circuitous and mysterious process operating through the world of our experience.

All these possibilities involve the operation of some mysterious factor in virtue of which our theories can be accepted as counterparts of laws of nature residing in the reality out there – something quite antithetical to the spirit of scientific realism.

I, for one, consider myself an adherent of the viewpoint of scientific realism where I use that term to mean *the reality of entities and correlations*, everything else being relegated to our phenomenal world and our interpretations of it. As part of this interpretation, we assume that *interactions* occur between the phenomenal entities that generate the impression of their properties and regularities of behavior, and in a further surge of philosophical fervor, one may go on to assume that these interactions, properties, and theories, all have their counterparts in reality. But being generated by reality is not the same thing as having counterparts there.

But there are trends in scientific realism that find it hard to desist altogether from notions generated in fervor: unless there is some regularity inherent in nature in the form of laws, how can our theories be so highly successful in explaining our experience and in predicting so accurately the behavior of phenomenal entities?

Here, however, one must be loyal to the lessons learned from complexity. A vast number of models of complex systems have by now been analyzed in mathematical terms and in more general approaches involving algorithms and computations, including ones based on AI systems that are endowed with learning abilities. All such studies point towards one single feature that all these systems have in common – all are characterized by a enormous range of spatial and temporal scales showing a multitude of stable regimes of behavior existing in space and time. The ‘regularities’ of the phenomenal world reflect one or more of the stable structures in one or more of such scales.

> As mentioned several times earlier, the term ‘space’ means one made up of possible states of a system that can be of an arbitrarily high dimension. Every stable regime has its own effective state space and refers effectively to some subsystem generated as a projection of the entire system on to some lower dimension that captures the stable behavior in question.

The reality out there is the *ultimate* in complexity, and it is completely beyond our conceptual ability to capture all these spatial and temporal structures that possibly characterize the noumenal reality in its present state of *self-organized complexity* (see below; see also sec. Complexity: a brief outline). It is highly likely that our mental apparatus – almost infinitely complex as it itself happens to be – and our scientific set-ups can access only a few of these regimes, and our theories, obtained by a method of abstraction from the world of our experience reflect the regularities of only these few regimes. It is essentially philosophy in fervor – out to resist contamination from what is referred to as anti-realism – that *projects* the regularities captured in our theories to 'reality at large'.

Scientific realism tolerates much debate and dissent within its own fold, but it gets emotional and puts its foot down when it comes to the question of the *truth* of theories supposed to describe the mechanisms underlying the workings of nature. Theories, according to major trends in scientific realism, may be revised from time to time but that is only because of our limited means in grasping the vastness and the intricacies of Nature, in virtue of which there always remain a gap that succeeding waves of theory building and theory revision are to bridge in the future. As these major trends claim, relinquishing the claim to truth is taken to stand for an attitude of pessimism and surrender.

But I must not myself get carried away in my own fervor and project myself as a critic of these major trends. Viewpoints are not to be fought over, as we must constantly keep on reminding ourselves. My worry is not over the correctness or otherwise of the position I adopt (such correctness can never be proved on hard evidence), but over the tendency of maintaining a sharp and irrevocable divide between what are described as 'scientific realism' and 'anti-realism' based on the single issue of locating truth in our theories and seeking a correspondence between these theories with purported 'laws of nature'. The assumption of the existence of such a sharp demarcation is better avoided if we are not to get shackled under the weight of our own viewpoint.

The point of view of anti-realism makes no bones about asserting that theories are mental constructs, and it may be argued that the position I adopt is then one adopted by anti-realism. I have no issue with being identified with this camp of philosophy or that – the practice of attaching tags to philosophical positions has its uses but cannot be stretched too far.

> I have stated that points of view cannot be fought over. But that must not mean that *discourse* over points of view is pointless. A philosophical mindset is a durable thing and does not go away overnight. But we are not born with our respective points of view – these are generated in the course of our journey through life, depending on how we confront and look at our accumulating experience. Likewise, points of view can change as well – in the course of experience once again, and by discourse and communication. There is no point *fighting* over points of view, but one can certainly try to *understand* a contrary point of view without being *dismissive* of it. Only then can a *synthesis* of the contraries be brought about, freeing us from permanent bondage to some mindset or other.

This is where I have to pause and, once again, summarize my take on the point of view of scientific realism as outlined up to this point of the present essay – I will add to it in subsequent sections.

> Scientific realism accepts the mind-independent existence of a reality made up of *entities and their correlations* – the two being inseparably linked into an integral whole. Myriads of signals of an enormous diversity are received by our senses and our instruments, from which is generated a huge canvass of *interpretations* of this reality in our mind. Reality in itself (the noumenal world) is known to us solely in terms of our perceptions and our interpretations, that form the phenomenal world. The noumenal entities and their unfolding correlations generate the experience of phenomenal entities, their interactions, and their behavior. One can, in principle, think of a correspondence between the phenomenal entities and their behavior on the one hand, and noumenal entities and their correlations on the other.
>
> The reality that generates phenomenal sensations in us is an infinite dimen-

sional and complex system, parts of which are captured in our conceptual world through these sensations. In keeping with the behavior of complex systems in general, that reality is co-evolving along with all its components and their correlations, and develops a multitude of *structures* made up of stable and unstable components in a multitude of *scales*. It is precisely the constituents in some stable components in some particular scales that we sense as the entities captured in the phenomenal world in any given context. Thus, what appears as a table in the context of our ordinary everyday observations, appears as a collection of molecules in a different context of observation on a finer scale.

Theories are formed in our mind by a continuous process of abstraction involving inductive and deductive inference (a special class of inductive processes is referred to as abduction). It is the theories that play the essential role of sorting out the complexities of behavior of entities that we experience, of making sense of that experience, and of providing us with explanations and predictions. Strictly speaking, theories are applicable to *models* constructed out of our experience by simplification that allow us to define these with precision and apply precisely defined rules of deduction from these theories – the precision being understood in relative terms. The consequences deduced from theories are compared back with our experience, thereby resulting in a process by which we make sense of our world and adapt ourselves to it.

Theories are constructs in our mind and do not necessarily correspond to counterparts in the noumenal world. The purported ’laws of nature’ residing in the reality beyond our mind are suppositions based on a projection from the phenomenal to the noumenal world. This goes against the fact that theories constitute the distilled essence of our experience constructed in a process of abstraction. Theories, moreover, are applicable to models that are incomplete and partial representations of the phenomenal world in the sense of being obtained as simplified versions of parts of the the latter. In this sense, theories are relevant as *locally* valid (in space and time) coded descriptions of the phenomenal reality.

> The questions that now remain are, is their a *global* theory valid for the entire phenomenal world of ours, embracing all the local versions? And, is there a *corresponding* grand unified law of nature? I have no answer to these questions since, for me, these do not carry meaning – theories are mental constructs of a local nature and have no counterpart in the noumenal world. It is here that my position bears a strong resemblance to anti-realism. Nonetheless, I still consider myself a realist in virtue of adopting the assumption of a mind-independent reality, as I have stated above in clear terms.
>
> We will have occasion to briefly discuss this again later in this essay (sections Theories of reality: in search of the 'ultimate theory', Summing up: complexity in reality).

This brings us to the concluding part of the present paper where we will look at a number of issues arising from the above position regarding reality and our conception of it, notable among these being the question of successive revisions of theories.

Theories of reality: in search of the 'ultimate theory'

We begin by recalling that theories are mental constructs that apply to models, that models and the theories applying to those are contextual, that various different models refer to different cross-sections of the phenomenal reality, and thus, to different parts and different cross-sections of the noumenal reality too. We recall also that a theory pertaining to a model is a distilled essence of observations made on it, arrived at by a process of abstraction and abduction.

Theories, in addition to being partial and contextual, are often found to require *radical revisions* from time to time. This is a matter of major discomfort to dominant trends in scientific realism. In the present section I am going to put forward my take on this vexed question in scientific realism, when a number of related issues will also come up for consideration, based on the standpoint I have outlined in the previous pages of this essay.

Theories are contextual and domain-specific

We first note a few examples that tell us how and in what sense theories apply to models, and are contextual and domain-specific.

Domains refer to specific areas of inquiry in our scientific endeavor. Thus, physics, chemistry, biology, medicine, geology, meteorology, social sciences, economics, business administration, governance, all are instances of domains. Among these, the social sciences, governance, business administration and such other domains were not traditionally considered to be related to science. But these are now routinely studied with the help of high-powered computers in terms of network representations of complex systems, and theories are routinely formed and applied to such systems. *Psychology* and the behavioral sciences form an interface between the domains of the physical and the social sciences.

Domains are made up of sub-domains. Thus, physics has innumerable sub-domains such as electromagnetic theory, gravitation theory, statistical mechanics, and so on, where there are further sub-divisions too. As sub-domains make up domains, the latter in turn can be grouped into broader fields where each field has certain common foundations and common methods, with broadly common features in the structures of their theories. Indeed, these broader fields, along with the domains, sub-domains, and the sub-divisions of the latter, can all be looked upon as forming a complex system among themselves, that can be represented in terms of a network having a hierarchical structure, as revealed in the multiplicity of journals devoted to general subject areas and to specialized topics, and in the papers published in those.

Theories are to be found in the papers published in the various journals, where the lineage of the theories can be traced from the domains and subdomains these papers refer to. Taking, for instance, a domain in physics, such as electromagnetic theory, one can see that there are innumerable sub-domains (and further sub-divisions too) with corresponding *theories* such as short wave asymptotics (i.e., ray optics), interference, diffraction and scattering theories, theory of antennas and waveguides, non-linear optics, quantum optics, and so on. There is a sense in saying that all these theories (with some exceptions that are based on the quantum theory of radiation) are just special topics within electromagnetic theory, but that does not go against the observation that each of these require special and specific approaches, and journal papers devoted to any two of these special topics bear little resemblance between them. It is very much a matter of *context* as to how one is to look at a theory devoted to any of these special topics – as a distilled essence of investigations into phenomena relating to the sub-domain (or a sub-division of a sub-domain), or as a part of a bigger theory.

There is a *correlation* between all these theories, and actual *structures* inherent in reality – the noumenal reality, as we have called it, where the terminology is borrowed from Kant. As mentioned earlier, reality is a hugely complex system – the *ultimate* in complexity, made up of an infinite multitude of dimensions, i.e., the number of independent entities required for a complete description of it which, truly speaking, is an impossible limit to achieve. It is, moreover, a dynamic system characterized by the feature of *co-evolution*, where all its components and their correlations evolve in a mutually determined manner. In consequence, reality is endowed with an infinite multitude of self-generated stable and unstable *structures* at an infinite multitude of *scales* in space and time. This, at times, is referred to as *self-organized complexity* (see, for instance, [29], and references therein) – in a loose manner of speaking, one can say that various different parts of a complex system passes through successive stages of self-organized criticality – there can be even be a large number of simultaneous instances of such transition in various different regions of the phase space, with self-organization emerging in between successive episodes of criticality – resulting in a huge canvass of self-organized complexity.

Instances of such structures and scales are to be found in solutions to sets of non-linear differential equations (see [13] for background), mostly obtained in numerical computations. All these structures at various different scales provide a multitude of different *contexts* in which observations can be made (referring to those that are accessible to our senses and our scientific instruments), experience gained, and theories constructed as distilled essence of experience.

What is the relation between all these theories in the various sub-domains and domains, all having some relation with actual structures existing in nature at various scales?

Theories pertaining to various sub-domains belonging to a given domain *dovetail* with one another, analogous to the way the languages and customs of different communities located in contiguous geographical regions are related, with overlapping features. All these languages and customs may have a common denominator, depending on the physical features of the region the communities are located in, and on the history of the migrating groups of people they are descendants of, but these common denominators do not determine the specific features pertaining to the communities. Likewise, theories pertaining to sub-domains may bear common birth-marks as descendants from a parent theory, but all are arrived at by *independent* processes of abstraction and abduction from experience gained in the respective specific contexts. These may all even be embedded in an overarching theoretical framework, but that does not detract from their autonomy – the overarching theory does not determine the specific features of these 'smaller' (but not lesser!) theories.

The electromagnetic theory encoded in Maxwell's equations does definitely provide the ground in which the ray theory and the diffraction theory of optics have germinated, but both these have had independent histories of development, with independent processes of abstraction having led to these. Both can be shown to have a common lineage in the form of limiting relations to the electromagnetic theory, but they are in no sense *determined* by the latter.

> Individuals having distinct mind-sets start talking at cross purposes at some stage when they are engaged in a discourse, because they *construe* differently – words and phrases carry different *meanings* for different people. This, does not, however, mean that communications and attempts at understanding one another must stop, having reached a dead end. Much of our understanding in this world depends on *tacitly* held views, where apparently contrary items of thought coexist without annihilating each other, integrated in our conceptual world – concepts have interpenetrating boundaries, while explicit statements show them as belonging to two incompatible groups of ideas, separated by a sharp boundary.
>
> The term 'determined by' or something 'determining' something else, results in a lot of confusion

> and misunderstanding. Do the Maxwell equations determine the theory of ray optics? Does the theory pertaining to the structure of the DNA molecule determine the behavioral diversity among people? Does the Schrödinger equation determine the structure of a complex molecule? Does a code determine the decoded script and the consequences that the latter can lead to? In each of these cases, one has to understand the complexities of meaning hidden in any attempted response to the question – there is a sense in which the response can be either yes or no, with none of the two being wrong; and again, there is a sense in which the two together make up a complex response – one it is difficult to make explicit.

Complexities in meaning only result from the complexities of the system it is supposed to refer to. In the above instance, the complexities of meaning of the term 'determined by' depends on the enormous complexity of our conceptual space and then, eventually, to the complexities of the parts of reality the term refers to. Thus, the electromagnetic theory encodes the behavior of electromagnetic fields in general while the ray theory encodes the behavior of short wavelength fields – the unpacking of the theory in the two cases describe the complex behavior of systems of which one is a part of the other, but the very complexity of the systems prevent the corresponding theory from being redundant. In other words, *complexity resides at all levels* and leads to the necessity of theories to be developed independently though, possibly, with one (ray theory) being enveloped by another (Maxwell theory), with the latter being in the nature of an overarching theory. As an analogy, one can think of a novel by a great author with a complex plot spanning a huge spectrum of space and time, and with a sub-plot in it describing the intricate relation between a man and a woman that is itself a deep and troubled one – a relation that is in the nature of a hopeless tangle, generating a multitude of contrary emotions that can never be resolved.

Every theory has to have a *context*, even though of a vague and no-specific nature. And the context goes a long way to set the entire tone and texture of the theory. In other words, theories that dovetail with one another may nevertheless have different contexts and very different *structures*. The ray theory describing the behavior of short wavelength electromagnetic radiation has a completely different structure when compared with the quantum theory of radiation where one has to take into account the interaction of radiation with matter. Or, again, take the example of a group of men in a religious congregation and one in a political demonstration. Even when the two groups of men have a common cultural background, the (vaguely formed) theories that generate our anticipation of the behavior of the two groups are completely different, though the two behavior patterns are only apparently incompatible with each other and have underlying common links. This last observation goes to show that theories are only incomplete guides to understanding the behavior of complex systems.

Emergent properties and emergent theories

We recall how complex systems are often characterized by *emergent properties*. Emergent properties are commonly associated with emergent *structures* appearing in the ceaseless dynamics of a complex system arising out of the varieties of interactions among the constituents at various levels of the system – and both, in turn, are associated with *emergent theories*.

As stated several times above, stable and unstable structures in a complex system appear at all scales in space and time. These stable structures are the ones that are perceived as the various ‘levels’ of organization of complex systems referred to earlier. Such levels emerge in the course of dynamical evolution of complex systems and can be perceived in various different contexts. For instance, the unconscious mind of an individual and its interaction with his conscious mind are explored by a psychologist in her consultation room, while the interaction of many such minds assumes relevance for the manager of a business organization. Decisions and policies of many such organizations, on the other hand, affect the economy of an entire country. At each such level, there is a measure of decomposability, i.e., the subsystems or the constituent units interacting with one another have an identity of their own. It is their interaction, along with the interactions with external systems (external to the system of interest, that is), that determine the behavior of a complex system perceived at some particular level.

As an instance, the properties of a liquid in bulk are determined by interactions of its constituent molecules and also its interactions with surrounding systems such as the atmosphere. Likewise, the properties of the molecules arise as consequences of the interactions among the electrons, protons, and neutrons making it up. However, the interactions between the electrons, protons, and neutrons are not directly involved in determining the bulk properties of the liquid, as determined by the interactions among its molecules. Moreover, the behavior of the liquid under diverse circumstances can be described mostly in terms of its bulk properties (such as its density, viscosity, compressibility) without direct reference to the molecules – these bulk properties emerge as *statistical* averages of molecular interactions. One then says that the bulk properties are *emergent* ones as these are independent of the *details* of the molecular interactions. On the other hand, the *theory* describing the properties of the liquid – one which links these bulk properties to averages over the molecular interactions – is an emergent one with reference to the theory describing the behavior of the individual molecules. All this, along with the observation that the liquid state itself emerges in a phase transition from a gaseous aggregate of molecules, establishes the statement that emergent structures, emergent properties, and emergent theories are all linked by a common thread – the one of *complexity*.

The theory of the liquid state (let us call it the 'A-theory') is an emergent one with reference to the theory aimed at establishing the structure of molecules (the 'B-theory', for easy reference), based on quantum mechanical principles. Broadly speaking, the two theories share a common ground but apart from this common lineage, they have little in common with each other – they are, in a manner of speaking, *independent* theories. Certain basic ingredients of the A-theory (ones relating to the inter-molecular potential) can be understood in terms of the B-theory, but that is about all though, of course, both the theories share the common language of physics and mathematics. There is sense in saying that the A-theory emerges from the B-theory though, here again, there is a certain reverse relation in that certain features of inter-molecular potentials can, to a certain extent, be inferred from the behavior of liquids.

The question arises as to whether and in what sense the A-theory can be said to be *reducible* to the B-theory. This is a question relating to the deep and complex relation between theories, analogous to the one of the complex inter-connections among our *concepts* – and is ultimately related to the complexity of reality itself. There is no easy or ‘satisfactory’ way of settling this question, as indeed there can never be.

All our theories arrived at in scientific investigations form a hugely complex system, analogous to the enormously complex webs of our beliefs and our concepts formed in the course of our accumulating experience in this world. Some of these theories are nested within others, some broadly imply others, some are in the nature of interpenetrating theories, while some are distant kin of others. In this complex web of theories that is an incessantly evolving one, there are structures on all scales, but no theory can be said to be the ultimate foundation of all others. Theories, in other words, are somewhat like words whose meanings are explained in a dictionary, where the meanings are explained only by *mutual* reference. For instance, the words ‘ball’, ‘sphere’, and ‘round’ can be found to occur in the entries for all the three. In other words, there is no *basic* or foundational set of words in terms of which all the others are explained. There may, however, exist certain groups such that, in each group, only a few words are mostly used to explain the meanings of the rest. This is because words correspond to concepts and categories as these are formed in the course of our experience, and experiences come piecemeal, having no systematic tree-like structure in them.

A theory is an abstraction from experience, with the latter pruned and idealized suitably so as to constitute a model – this happens with scant regard to the currently existing structure of the network representing all the accumulated theories in various different fields, domains, and subdomains.

Two questions that stand out are the following: *first*, if theories are mental constructs, then how come they are so successful, and *next* why should all the theories in the various domains and sub-domains of experience not ultimately reduce to a single grand theory of the universe as a whole – some ultimate theory of fundamental particles and fields coupled with the theory of gravitation so that the small scale and large scale theories of the cosmos are accommodated within it? Related to these two questions is the one that asks whether the successive revisions to a theory lead us closer and closer to truth about some part of nature, with all these partial truths embedded in one single all-embracing *foundation* of all theories?

None of these questions can ever be settled conclusively and to the satisfaction of all because these are related to the metaphysics and to the ontology one is prepared to accept. The way I see it, one has to take as guide the lessons grasped from our experience of complex systems.

A complex system involves levels and layers nested within it, and can only be experienced partially – in bits and pieces. The question of looking at the behavior of a complex system *in its entirety* is an abstract one because of the infinitely extended web of links to other systems equally complex, and to systems at levels located higher and lower in the hierarchy – indeed, even the idea of a single hierarchy is an abstract one, since all the 'hierarchies' are tangled together in this world of ours.

While we have focused here on the relation between emergent properties and emergent theories, the idea of emergent properties has led to questions being asked as to whether it is a philosophically and logically sound one. Scientists and philosophers subscribing to the viewpoint of reductionism complain that 'emergence' has a mystical aura about it that does not bode well for either science or philosophy. In this essay I adopt the position that one needs to have a better understanding of emergence from the scientific point of view – how emergence is related to co-evolution and the appearance of stable and unstable structures on all scales in a complex system – before a more meaningful philosophical discourse can be engaged in. For background, I suggest [23], and [10], along with references cited therein.

> In this context, the following lines from Crick, quoted in [10], may be of some relevance:
>
> "There are two meanings of the term emergent. The first has mystical overtones. It implies that the emergent behavior cannot in any way, even in principle, be understood as the combined behavior of its separate parts. I find it difficult to relate to this type of thinking. The scientific meaning of emergent, or at least the one I use, assumes that, while the whole may not be the simple sum of the separate parts, its behavior can, at least in principle, be understood from the nature and behavior of its parts plus the knowledge of how all these parts interact." [8]
>
> However, this passage from Crick notwithstanding, I submit that, as of now, the deep link between emergence and complexity is not sufficiently well understood (on scientific terms, that is)

to make ‘in-principle’ statements as enlightening or meaningful as they should be.

Successive revisions of theories

Theories are arrived at inductively by abstracting from experience, and are revised as and when they fail the test of observations accumulating subsequently.

On the basis of clinical observations and pathological tests, my family physician diagnosed that my son was having a certain problem with his blood circulation (a ‘theory’). Treatment prescribed by him produced early results, indicating the correctness of his diagnosis. However, there was a relapse of earlier symptoms and a more serious symptom started showing. The doctor then patiently went through his history once again and came up with a completely new diagnosis (the revised theory). A new course of treatment rapidly cured my son.

An inductive inference is, in principle, *defeasible* – the conclusions get modified under new evidence. As in the case of the medical diagnosis of my son’s ailment. And, the modification need not be ‘small’ in any sense. As one arrives at a new inference in the place of an old one, the latter may differ quite markedly from the former. An alternative way of saying this is that an inductive inference is *underdetermined* by evidence – alternative choices are possible on the basis of one and the *same* evidence, and an added evidence may tilt the balance away from an earlier one to a novel and more justified alternative. But the justification is never complete.

Early on in my life I chose the career of a teacher – unfolding circumstances propelled me to a research career; and then, finally, I left that too so as to adopt the life devoted to social work – all this while choosing from among alternatives that life presented to me, and finding one choice better than an earlier one under added experience gained in my life’s journey.

But perhaps hard scientific evidence and well-tested theories are not like these chaotically changing choices so common in our social experience? Surely, the fact that the gyromagnetic ratio of the electron is known correct to twelve decimal places makes it an essentially accurate conclusion of the current quantum field theory, possibly open to only extremely small corrections under the impact of further evidence and further revision of theory?

I am no expert to comment upon the current state of affairs with the standard model that has successfully explained and predicted a wide range of phenomena at the subatomic level, and on the efforts under way to patch up its loopholes, but I can only say that the 'loopholes' appear to be gaping ones when I come across and read popular accounts of those (see [30] for a detailed and serious assessment, one that is not too technical).

Here, to put things into perspective, I will point to the spectacular accuracy with which Newtonian mechanics, along with Newton's law of gravitation, explains and predicts the orbits of gravitating bodies that makes space travel possible. And I will also point out that Newtonian mechanics, including the relativistic corrections and possibly also the corrections due to the space-time curvature caused by the sun's gravitational field is a marvel of a theory, but only *within a context*. And *that* context differs equally spectacularly from the one in which the collision data from the large hadron collider at CERN assume relevance. In other words, the stupendous success of either of the two theories – the Newtonian theory with appropriate corrections and the Standard model – both are contextual and are arrived at independently of each other (in a manner of speaking, that is) – the infinitely complex reality existing out there has space enough to accommodate both and, who knows, many many more.

I will not speculate on whether a possible future theory will connect up gravitation with the standard model not only because I have absolutely no competence for such a thing, but no less pertinently because the job that I have set for myself in this essay is the much more modest one to see how the lessons learned from our experience with complex systems help us on this issue of inter-theory relations and theory revision.

The accuracy of the predictions of a scientific theory is contextual, and so, in a sense, is the explanatory power. The gyromagnetic ratio of the electron arising from its spin was found to be ‘anomalous’ (as compared with the value of the ratio arising from ‘orbital’ motions of the electron) in connection with spectral characteristics of atoms, but it could not be determined with very great accuracy within the context set by spectral studies. A remarkable improvement was made possible within the context of quantum field theory. The important thing to note is that the improvement in accuracy was, in some sense, ‘small’ so that the succeeding theory (quantum electrodynamics, and then, the standard model) could be interpreted as a ‘small’ correction over the preceding one (quantum mechanics), but the frameworks of the two theories differed spectacularly. In other words, the ‘small’ difference in the value of the gyromagnetic ratio was symptomatic of a very big structural revision in the theory. Quite often, a succeeding theory, in addition to being responsible for small corrections in predicted values, unearths altogether new phenomena as in the case of quantum field theory predicting and explaining the existence of new sub-nuclear particles. In that sense, then, not only the terms of reference of the new theory, but its predictions too differ to a large extent from those of the earlier one.

This once again raises the question as to whether successive revisions of theory can be considered to be in the nature of ‘small corrections’, indicating a convergence to some final theory describing reality.

This is a question that cannot be settled one way or the other to the satisfaction of everybody since the answer depends on the meanings that one attaches to phrases like ‘small correction’, ‘convergence’, and so on, and these meanings, in turn, depend on the metaphysics that one has in mind such as theories being the reflection of an underlying ‘regularity’ and ‘harmony’ of nature. As for me, I do not find myself impressed by the idea of regularities and harmony buried deep within the bosom of nature. The idea of regularities and harmony is specific to our thinking mind which is always interpreting, sorting, always formulating ‘simple’ rules for our survival and onward journey in life. What I consider as ‘ultimate’ in nature is, precisely, its complexity – a complexity that generates islands of regularity within itself that we get a hold on, but ones that cannot be said to be indicative of ‘intrinsic harmony’ of Nature.

The only safe extrapolation – if there could be one – from our experienced phenomenal reality to the ‘real’ reality out there is the one of complexity, of an immense spectrum of interactions among its constituents when looked at within any given context, where the term ‘context’ is now used to mean a given level of self-organization of the infinitely tangled system that we refer to as the noumenal reality.

As a complex system, reality is a *co-evolving* one, where the entities it is made up of keep changing, their interactions keep changing, and their levels of self-organization keep changing. What we can observe of this reality is, by its very nature, some chunk of it within a limited horizon of space and time, however vast and varied that may appear to us. As we focus on some part of reality, we seem to zero in on some regularity inherent in it and may have the feeling that our theories, in the course of successive revisions, are approaching the point of correctly capturing that regularity. But on actually approaching that point, the convergence seems to dissolve in thin air and ‘divergence’ raises its ugly head. This happens because, with accumulating experience, *a new context opens up.*

> Within the confines of purely combinatorial considerations, one can refer to *Ramsey theory* ([4]), results in which imply that within every structure, there has to exist a regular or ordered substructure. This, admittedly, is a vague and incomplete paraphrasing in a subject that has attracted attention of great mathematical minds and has had interesting applications, but will have to suffice for our present purpose.
>
> In the present paper we have focused on the dynamical evolution of networks, whose nodes (or vertices) represent systems that interact with one another, as represented by the links (or edges) in it. As we have mentioned, a network representing a real-life system is generally a multi-layered one and undergoes co-evolution. In this process of co-evolution that is likely to have disordered and ordered aspects built into it, the network passes through a succession of structures where, looking at the structure at any particular stage of the process, one can find ‘islands’ of regularity, in accordance with results in the Ramsey theory.
>
> Turning our attention to the infinitely extended and infinitely complex noumenal reality, one imagines that our scientific theories capture the order and harmony built into these islands of regularity within a vast sea of complexity. Evidently, there is nothing to guarantee that the order inherent in these islands of regularity can be extrapolated to nature as a whole.

Our experience of reality always occurs within the constraint of certain borderlines that are, in a sense, objective ones – objective, that is, with reference to the current context in which science can access the universe in space and time. For instance, even the hugely successful standard model of fundamental particles and their interactions works within the context set by what is referred to as the *Planck scale*. The science of fundamental particles and their interactions, along with the theory of the 'early universe' ignores all inhomogeneities and structures of the noumenal world down to the atomic scale and strives to access even smaller distance and time scales by using highly energetic particles as probes, investing fabulous amounts of resources into the job. The idea is to explore the possibilities of a theory that fits with the standard model at the scales of length and energy currently accessible and, at the same time, makes it complete by weaving gravitation seamlessly into its fabric. Whether and to what extent that effort is going to meet with success is anybody's guess. Meanwhile, the Planck scale sets the context of the standard model – what lies on the other side of it can only be conjectured. This little essay of mine is meant to make a statement that the complexity of the real world has to be reckoned with in setting our mind on what to expect and how to direct our efforts on this issue of extending the standard model.

In stating that the context to our theories are not arbitrarily chosen by us but are set by objectively determined limiting boundaries, what one means is that these boundaries depend on the part of reality the theories try to probe and access, and on the current state of organization of that reality. It is in this sense that the limits within which the standard model is expected to work can be said to be related to the Planck scale because that sets the context within which gravitation can be included in the theory as a *classical* field, independently of the quantum mechanical interactions among particles – interactions of the electro-weak and the strong variety.

Instances abound where a theory gets modified to a 'large' extent as some objectively set boundary or other is crossed and discrepancies with observed facts emerge that may be either 'small' or 'large' ones. Even where a small but persistent discrepancy makes necessary the modification of a theory, one eventually finds that the terrain on the other side of the objectively existing boundary setting the context of the earlier theory is replete with phenomena quite out of the range of capabilities of that earlier theory. In this sense, the revision of an existing theory can be said to be substantial or extensive in respect of both the framework of the theory and its terms of reference *and* the concrete predictions of the theory.

This is what appears to be the case of the general theory of relativity as it emerged as a revision of the Newtonian theory of gravitation. Even as the terms of reference of the revised theory differ markedly over those of the earlier one and entirely new conceptual ingredients are introduced, the predictions of the two theories differ to only a small extent over relatively small scales of space and time. However, when looked at over larger scales and in the presence of gravitating bodies of relatively large mass (one can attach quite specific meaning to the terms ‘small’ and ‘large’ here though I will not enter into it), the general theory makes predictions that differ spectacularly from those of the Newtonian theory, in keeping with the remarkable difference in the conceptual framework of the two.

The relation between an earlier theory and the revised one is *asymmetrical* – referring to the border separating the two theories (the one corresponding to small velocities and a small strength of the gravitational field), the predictions from the revised theory approach those from the earlier theory as one approaches the border in some limiting sense (where the former reproduce the latter along with small correction terms), but the converse does not hold. As one other instance of such a relation between an earlier and a succeeding theory, one can refer to the motion of a particle approaching a ‘potential barrier’ as described in the classical and quantum theories. In the classical theory, the particle fails to propagate to the other side of the barrier, while in the quantum theoretic description the particle ‘tunnels’ to the other side, though the probability of tunneling decreases exponentially as the height and width of the barrier become large in comparison with its energy in some well-defined limiting sense (the same limit corresponds to the Planck constant going to zero). In this case, the two theories differ spectacularly in their conceptual framework, and an asymmetry is quite manifest: the predictions of the quantum mechanical theory makes it possible to understand and interpret those of the classical theory close to the limiting situation mentioned above, but there is no way the classical results can be used to interpret the quantum mechanical ones in an analogous manner.

This asymmetrical relation finds expression in certain special features of the predictions of the revised theory close to the border setting the two theories apart, since the border is seldom a sharp one. These special features can be described in mathematical terms in the case of theories in the physical sciences. As one moves across the border, or approaches it on one side, quantitative prediction can be expressed in terms of an *asymptotic series* instead of a *convergent series* commonly encountered in mathematical approximation schemes. This corresponds to the fact that the relation between theories can often be described in terms of *singular limits*.

Digression: Asymptotic Series and Singular limits

Asymptotic series

A *convergent series* is one where one can sum up an infinite number of terms. In principle, one can perform a term-by-term addition to obtain successive *partial sums* of the series, which approach as close as one wishes to a fixed number – the *sum* of the infinite series in question. Each partial sum differs from the sum of the series by an 'error term' that gets smaller and smaller as successive terms of the series are summed up.

Innumerable examples exist of such convergent series representing mathematical and physical quantities of interest. One such object is the number 'pi' (π), the ratio of the circumference and the diameter of a circle. In decimal terms it is approximated by 3.14159265, but this value differs from the actual value of π by a small error term – the error never vanishes even when one fills up a large number of decimal places. There exist several convergent expansions where successive partial sums approach π at a rapid rate.

Convergent series are useful not only to represent numbers but *functions* as well. Thus, a function $f(z)$ depending on the variable z (commonly one taking up complex values of the form $a + ib$, where a, b are real numbers) can be represented by a convergent series for every specified value of z within some specified domain.

Contrasting with the case of convergent series, there exist examples of infinite series – of great relevance in mathematics and the physical sciences – that are endowed with *contrary* significance. Such a series, referred to as an *asymptotic series*, can be used to approximate a function with great accuracy but is typically a *divergent* one. Thus, a series of the form $(a_0 + a_1z + a_2z^2 + \cdots + a_Nz^N + \cdots)$ can be used to approximate a function $f(z)$ at a point z in some neighborhood of the point $z = 0$ by evaluating the partial sum up to an optimum order $N = N(z)$ (where it is possible to estimate $N(z)$ quite accurately), but on evaluating the successive partial sums beyond $N(z)$ one finds the series to diverge. Early exponents of the power and potentiality of asymptotic series were George Stokes and Henri Poincare among others, who reinstated these divergent series in the road map of mainstream mathematics and physics following a phase when these were banished from respectable research programs.

Singular limits

The noted mathematician-physicist Michael Berry illustrated the idea underlying a singular limit by means of the following interesting observation, made in a light spirit: half the bodily remains ($\delta = \frac{1}{2}$) of a worm discovered in an apple after a big bite is more revealing (and revolting too) than a full worm ($\delta = 1$) since it indicates that the other half is now residing in your digestive tract; by the same token, say one-tenth of the remains ($\delta = \frac{1}{10}$) is even more revolting, and so on, till you discover to your delight that one of the apples in the lot does not reveal a worm ($\delta = 0$) even after several bites, because that indicates that the apple is *worm-free* (discounting the other appalling possibility). Here $\delta = 0$ is a *singular limit* since something entirely novel emerges in this limit as compared to small values of δ, close to it.

Other well-known examples of the phenomenon of singular limits in physics are: the limit of the viscosity of a liquid going to zero (no turbulence in the singular limit), the limit of wavelength of light going to zero (in relation to the size of an obstacle; no interference and no diffraction fringe), the Planck constant going to zero (in relation to the size of a typical action integral; classical mechanics: no tunneling through a potential barrier, no explanation for the hydrogen spectrum, ... no nothing).

Berry and a number of other mathematicians and physicists (see, for instance, [5], [7]) have worked on what a theory looks like *close* to a singular limit because the limit itself is not smooth, and it is of great interest to know what transpires close to the limit ($\delta \gtrapprox 0$) as against the situations corresponding to $\delta = 0$ and δ substantially away from zero. This sheds much light on what is referred to as *theory reduction* – a singular limit corresponds to some limiting value of a relevant parameter (denoted by δ here), close to which a theory assumes a complex form. The complexity, originally hinted at by Stokes, melts away as δ takes up the value zero and also as delta moves substantially away from zero where, however, the theory is of a notably different structure.

More generally, singular limits illuminate the *transition* between different *levels* of reality – they tell us how the levels differ 'qualitatively' and yet can be understood in terms of the continuous variation of a single parameter δ (or of a number of parameters). They tell us that the qualitative difference is the result of a certain 'violent' behavior close to the limit – a violence that can nevertheless be understood in terms of the smooth variation of a single parameter. What is more, this violence can typically be related to the appearance of an *asymptotic* series describing some typical physical prediction of the theory.

The truth of theories

At this point, we look at the idea of *truth* inherent in a theory. The concept of truth is a vexed one. Even within the rigorous domain of mathematical logic, it is difficult business arriving at a precise formulation of what is meant by truth. This is achieved within the framework of the *correspondence theory* of truth built up, among others, by Alfred Tarski.

Truth is a property characterizing a statement (a 'sentence' in some formal language) but is semantic in nature. In other words the truth of a statement says something about the state of affairs in some ‘universe’ of discourse, i.e., some set in the context of mathematical logic. Tarski derived the definition of truth from that of ‘satisfaction’. However, instead of following the rigorous logical route to the concept of truth, we follow the broad outlines of the formal approach (see, for instance, [17]) and adopt the position that statements derived in a theory (ones that can be taken to constitute a ‘language’) can be true if they ‘correspond’ to some state of affairs in a universe, where the ‘universe’ may mean our phenomenal world or some part of it that one may choose. The term ‘model’ as used in the present essay is, in a broad sense, analogous to what is referred to as a model for a set of sentences of a formal language: a model (relative to a scientific theory) is some part of the phenomenal world defined contextually in which the statements derived from the theory turn out to be true. Here the term ‘truth’ means that a state of affairs in the model, *corresponding* to some particular statement derived from the theory happens to hold in the model. For instance, a system made up of a specified number of particles, imagined to be isolated from the rest of the universe, qualifies as a model for the theory based on classical mechanics along with Newton’s law of gravitation, but is not a model for the theory of electro-weak interactions.

An important observation on the semantic theory is that the truth of a statement acquires meaning only when it refers to some state of affairs *within* the universe under consideration, i.e., within our phenomenal world in the present context. However, a statement *about* that universe as a whole is not admissible as one whose truth can be ascertained. This is a stricture that prevents the *liar paradox* and other anomalies from vitiating the idea of truth as outlined in the semantic theory (also referred to as the correspondence theory).

However, it is not only the matter of a formal logical paradox that stands in the way of ascertaining that the entire phenomenal world of ours is governed by some ‘ultimate’ law, though it is certainly food for thought as to whether it is meaningful to talk of the truth of a statement pertaining to ‘nature at large’ since our world as a whole is not embedded in a larger world where we are located as observers. In other words, in stating that there is an ultimate law of nature, we repeatedly come across an impasse where we need the so-called god's-eye or god's-design point of view to bail us out.

A less divine option to adopt is to accept that there is no such thing as an ultimate law of nature – a point of view arrived at on the basis of lessons drawn from our experience. This is the experience that tells us that theories are constructed piecemeal and apply to models within specific domains of experience, a model being defined with reference to some part of our phenomenal reality delimited by means of a context that may be made explicit or else left implied. That same experience tells us that when our range of exploration and observation gets extended across certain objectively existing boundaries, a theory gets revised so as to explain anomalies and to accommodate new phenomena, and a broader theory emerges covering a newly emerging domain within our phenomenal reality. Of the two theories, the one arising in the process of revision is a broader one in that one can interpret certain features of the previously existing theory within its framework, but the converse relation does not hold. Further, the two theories have incommensurate features, and do not conform to the picture of a monotonic progression towards an all-embracing theory, valid across domains to the entire phenomenal universe.

> Further considerations on the issue of theory revision are to be found in sections Singular limits and Summing up: complexity in reality. In addition, refer to [19], where theory revision is considered with reference to a restructuring of our *conceptual space*.

There is a major trend in scientific realism that asserts that theories make true statements about reality, and in order to make this assertion compatible with the idea of a progression towards an overarching theory, there has emerged a trend to replace the idea of 'truth' by one of 'truthlikeness' or 'verisimilitude' as it is referred to. Apart from the question of how consistently one can formulate the idea of verisimilitude ([24], [2]), one has also to recognize that, instead of a monotonic convergence, successive waves of theory building may reflect the behavior of an asymptotic series that is found to converge only up to a point, after which it starts diverging. Past the point of divergence, an emergent theory can again converge to observed features of phenomena in an expanded domain only to diverge once again as some new boundary is crossed. It is this picture of non-monotonic and incommensurate behavior of successively revised theories that may make redundant the efforts at consistently replacing the idea of truth of a theory with that of verisimilitude.

Finally, truth is related with the question of *theory choice*. In contrast to the formal theory of truth, truth in real life is conditional on its *acceptance* by human society at large. This may sound paradoxical since truth of a statement is commonly supposed to depend on objectively existing ‘state of affairs’ in the world. But recall that the world we are speaking of is the phenomenal world where a statement pointing to an objectively existing state of affairs is, all said and done, a matter of interpretation. And, in this complex world of ours, one cannot simplify things by just saying that the interpretation concerned is the interpretation ‘of mankind’ and acceptance of truth of a statement is acceptance by ‘mankind’. This brings us to the domain of social reality where science is engaged in a complex interaction with human society. In mathematics, everything is formalized so that nothing is left to vagaries of human psychology (or, is it? – but we will let that go) and acceptance of truth is reduced to *proof*. Major logical systems are *complete* in the sense that one can produce proofs for all true statements. Real life is much more messy and innumerable conflicts among men prevent a universal yardstick for the judgment of truth – as a result of which elaborate legal systems have come into being.

In scientific exploration, the situation is somewhere in between where, broadly speaking, peer-reviewed journals constitute a system of establishing the truth of theories. In reality, the system is tolerably ‘objective’ so far as the acceptance of a major portion of the totality of all scientific contributions is concerned, but exhibits gaping loopholes when it comes to instances of *theory revision*. This is precisely because of the *incommensurability* inherent in successive theories that arise in what have been referred to as *conceptual* revolutions. As a result of the incommensurability, successive theories cannot be compared in their totality in terms of reference common to both since the succeeding theory contains new conceptual ingredients that the preceding theory lacks. It is here that the acceptance of theories depends to a major extent on *points of view* of various different groups of scientists and even among larger social groups. This is why the idea of incommensurability is, at times, branded as *social constructivism* – a point of view that is supposed to be inimical to scientific realism.

However, as I see it, scientific realism, in order to be consistent, has to make room for the idea of incommensurability. Looking at the case of what Thomas Kuhn calls a scientific revolution ([16]), conflicting points of view that can never disappear from human society can impede the acceptance of a theory only up to a point since there always exist common referents in the two theories close to the border separating the two that can be subjected to reality check.

Summing up: complexity in reality

> In this essay we have traveled far and wide, in order to see how our conception of reality is shaped by its complexity. We have at times been somewhat desultory and at times repetitive, partly because complexity is a messy thing – there is no neat, cut and dried account of how it operates. It is not inherently beautiful, elegant, or harmonious, though there are islands of simplicity, beauty, and harmony in it. In one's attempt at interpreting reality, one often has the satisfaction of getting to converge on to an elegant and beautiful theory when an extrapolation appears to be in order, extending the terrain ruled by simplicity, elegance, and harmony, and then, at some stage of extrapolation, one is met with blatant divergence. This then calls for a renewed hunt for elegance and harmony in a new terrain. This, as I see it, is the best that we can expect of science in its attempt at understanding and explaining reality – an infinitely extending mass of complexity that it is.

Even as I have offered partial summary of our wandering discourse on several occasions earlier in this essay (see, in particular, sections Reality and our interpretation of it, Theory as code, Ontology of reality: entities and correlations, Models and their significance, and Do theories correspond to 'laws of nature'?), I find it expedient to mention a few salient points of it before I finally call a halt, adding a few explanatory remarks on the way. In winding up, I'll go back to the question of incommensurability and to the one of a ‘final theory’ because these are where I feel that scientific realism continues to remain kind of hesitant and undecided.

1. Scientific realism is based on the idea that there exists a mind-independent reality (the ‘noumenal’ reality as we have called it) that is an infinitely complex system and is comprised of entities and their correlations – the two making up an inseparable whole that can be separated only notionally. Various parts of this reality send out signals, some of which are captured in our senses and our instruments wherefrom we have a perception that constitutes the phenomenal world. All our experience relates to this phenomenal world, which we interpret and sort out in the form of concepts, beliefs, and theories, the latter being specialized systems of beliefs – justified by evidence and accepted as true. Theories are meant to explain and predict the behavior of systems in the phenomenal world, where the systems and their interactions have a correspondence with entities and their correlations in the noumenal world.
2. Theories are domain-specific and are built up by a process of inference from observed behavior of systems, that behavior being generated by their interactions. They constitute, in a sense, the distilled essence of our experience and, strictly speaking, apply to *models*, where a model represents some specified chunk of reality with some specific *context* added to it – the context represents the effect of the rest of the complex reality. The very complexity of the reality makes a model sensitively dependent on the context. The truth or falsity of a theory is a question that can be settled only with reference to a model, defined in some context – however, the definition of the model along with its context may not be overtly precise, either or both being left implicit.
3. A model along with its context may, in a sense, be thought of as a *projection* of the infinite-dimensional phenomenal reality into some smaller domain – these projections being the faces of reality that we come to observe, depending on the limits of our senses and our instruments. The-

ories can then be described as constructs sorting out the behavior that we experience within these projections, and appear as codes from which their predictions can be obtained by a process of unpacking – one that often requires elaborate schemes of approximation. These predictions, on being compared back with experience, provide the reality check on the theories.

4. Predictions obtained from a theory can be astoundingly accurate, testifying to the remarkable effectiveness of the inferential process in which these are arrived at, and also to the fact that the models to which these apply are, despite appearances, actually simple ones where much of the complexity of the real world are left out. For instance, the Newtonian theory of gravitation augmented with corrections from the general theory of relativity applies to a system of massive particles, *with all other interactions imagined to be switched off and all other complex structures ignored*, and predicts to an excellent degree of approximation a vast range of phenomena. Some of the ignored structures are then introduced into the theory in successive stages of approximation, such as the rotational motions of heavenly bodies, considered as rigid ones (fluidity of the cores of these bodies can then be introduced in the next stage of approximation).

   All this is possible because of the decomposability property of complex systems that owes its origin to islands of stability generated in the process of self-organized complexity. An analogous situation arises in the case of the standard model which, after all, is a simple one (again, with credit going to the remarkable inferential ability inherent in the way it was arrived at), and is applied to scattering processes where the gravitational interactions and all other structure in the world are left out of consideration – these, indeed, do not matter in the domain defined by these scattering processes.

   As the context defining a model changes, as we look at some chunk of the complex reality from a different perspective, the behavior pattern within the model changes, and can change dramatically. This results in a notable change in the structure of the theory describing the model, though there may exist common referents in the two theories (the ones applicable before and after the context change) regarding which these give near-identical predictions. For instance, quantum electrodynamics introduces only a small (though crucial from a theoretical point of view) correction to the gyromagnetic ratio of the electron over the value obtained from atomic spectroscopy since the latter ignores certain complexities in the electromagnetic interaction that the former takes cognizance of. However, the 'small' correction notwithstanding, the theoretical structure of quantum electrodynamics differs spectacularly from that of non-relativistic quantum mechanics.

Small corrections or small anomalies that appear to be insignificant at first sight (another case in point is the Lamb shift of spectral lines) actually act as pointers to complexities of the world lurking behind the apparent simplicity of a theory just as specks of dust visible at the boundaries of a rug on the floor point to a big mess of dust hiding under it.

5. Thus, one starts from a theory applying to a given model within some particular domain of experience, constructs a theory, checks for the validity of the theory within the context of the model, and then proceeds to incorporate some more complexity into the theory by attending to anomalies that the theory cannot account for. This corresponds to a new model along with a changed context and, even as the model addresses apparently small anomalies, an attempt at a correct explanation of these uncovers a big change where hitherto ignored complexities come up for consideration. This is how theories are built and re-built. Successive theories leave unscathed some predictions regarding the behavior of systems since these relate to common referents within the domains of these theories, but the small corrections to these obtained at successive stages

of theory building are symptomatic of big changes in the structure of the theories arising from new complexities crowding in.

In other words, *predictions regarding the common referents of the successive theories may change in a commensurate manner, but the theories themselves are not commensurate.*

This can be illustrated by way of referring to the behavior of a solid. This behavior is captured in the spectral characteristics of the solid in various different ranges of the overall frequency spectrum (ranging from zero to infinity), as revealed by its response to various types of *probes* scattered from it and by a multitude of other types of response. One finds in gradual succession that the solid – a big chunk of complexity that it is – admits of a bewildering variety of *collective excitations* that can be uncovered only bit by tiny bit. At each stage, one sets up a theory applicable to a situation where only one or a few types of these excitations are relevant, as revealed by some simplified *effective Hamiltonian* (expressed in terms of the so-called *quasi-particles*), and then moves on to some other context where some other effective Hamiltonian describes a different set of excitations.

To be sure, the solid as a whole can be conveniently described by a Hamiltonian based on the electrostatic interactions between its charged constituents, shutting off all considerations of quantum electrodynamics and of the weak and strong interactions (where, in the process, electrons, protons, and neutrons are divested of possible internal structures, and gravitational interactions are ignored), but even this Hamiltonian, looked at as a code, is too difficult to unpack when the quantum mechanical symmetry principles on sets of identical particles (leading, among other things, to the Pauli exclusion principle) are taken into consideration. A piece of solid – a tiny chunk of the complex reality that it is – is a messy thing so far as a theoretical description of its behavior is concerned. One has to be content with a mosaic of 'small' theories, all differing from one another in their concrete ingredients, rather than one single overarching theory having a 'simple' structure.

As with the solid, so with the world of the so-called elementary particles. But here one lacks hard evidence in support of the viewpoint one holds (not that viewpoints are easily changed on the basis of hard evidence), because the wherewithal necessary for that is difficult to come by, even as fabulous – perhaps too fabulous – amounts are already being invested for the purpose. I will not comment on the investments being made because that is not under consideration within the confines of this essay since it requires a discourse, among other things, on the *power structures* linking science to the rest of the human society. As higher and higher energy scales are accessed in investigating the scattering events among particles, attempts at zeroing in onto a simple and all-embracing theory appear to prove futile ([30]), even though what appears to be futile to one may appear highly promising to others. The world of elementary particles is a complex one, carrying in itself the imprint of the complexity of reality at large, and lessons learned from the experience on complex systems are likely to apply here as well.

6. The incommensurability inherent in successive waves of theory building often appears in the form of *singular limits* in the transition from one theory to the immediately preceding one. Modifications in the predictions of a theory close to the border separating the domains of applicability of successive theories, commonly marked as 'small' corrections, are actually tell tale signs of incommensurability, in that these appear as terms in an *asymptotic series* symptomatic of a singular limit.
7. Let us now imagine a hypothetical scenario where various different domains of experience are separated from one another by borders described in terms of not one single parameter (denoted above by δ) but of a host of relevant parameters (say, $\delta_1, \delta_2, \cdots$). As some particular parameter (δ_1)

approaches a singular limit (say, $\delta_1 = \overline{\delta_1}$) from one side (say, $\delta_1 \to \overline{\delta_1}^+$), there appears an asymptotic series describing the value of some relevant physical variable, signifying the transition to a distinct theoretical framework appearing at $\delta_1 = \overline{\delta_1}$. The theory valid for $\delta_1 > \overline{\delta_1}$ on the other hand, involves other relevant parameters, any one of which (say, δ_2) becomes significant as some *other* border of reality is approached in an expanded domain of experience. The preceding theory corresponding to $\delta_1 = \overline{\delta_1}$ (for concreteness, one can think of δ_1 as the Planck constant $\hbar$, for which $\overline{\delta_1} = 0$) is also characterized by a similar border corresponding to some other physical parameter. Successive waves of theory building may correspond to such incommensurate transitions, as a result of which mankind goes on to build up a mosaic of theories in its perennial attempt at sorting out and making sense of the enormous complexity of nature that it is confronted with.

8. It remains to describe and understand the *asymmetric* relation between theories built in order to explain the behavior of systems within models appearing in successive stages of expansion of our domains of experience. This is the problem commonly referred to as 'theory reduction' where a theory 'A' appears to reduce to a relatively simpler theory 'B' as some parameter (say, δ) approaches a singular limit (say, $\bar{\delta}$). The 'simpler' theory obtained with $\delta = \bar{\delta}$ can, to a certain extent, be understood in terms of the reducing theory 'A', but only in a close vicinity of the limiting value $\bar{\delta}$, though the converse is usually not true – the terms of reference of the theory 'A' cannot be understood within the folds of the theory 'B'.

   However, the theory 'B' may, in turn, involve additional parameters that may correspond to similar transitions to other theories none of which are, however, related to the theory 'A' in an analogous way. This is how science builds up a mosaic of theories that in itself constitutes a complex system – a reflection of the complexity of Nature at large.

9. It is here that we point to the internal *structure* of a theory that helps us

understand how two theories may be incommensurate with reference to each other and still have a set of common referents and a common set of ideas underlying both. Theories are made up of *concepts* correlated with one another by a multitude of relations of association and implication. The totality of these correlated concepts forms, in turn, an immensely complex network where, moreover, the network is a *multi-layered* one involving several layers of relations among the concepts. For instance, there is one layer where the relation between concepts is expressed in plain language without scientific connotations, another layer expressed in mathematical terms, another one expressed in terms of theory with a limited domain of validity, still another layer expressed in terms of a broader theory, and so on.

The conceptual network is a *co-evolving* one, along with the structure of the concepts and of all these layers, where some concepts and some layers are added afresh, some retained, some get modified, and some get deleted as obsolete. In other words, in the event of a theory revision, some of the layers remain substantially intact while some other are modified in major ways and still other are added afresh. It is the set of concepts and layers of correlation that remain substantially unaltered that provide a common ground of mutual reference between the theories while the modifications and fresh additions constitute the relation of incommensurability between the two.

It is precisely this that incorporates the viewpoint of incommensurability within the framework of scientific realism without relegating it to the domain of social constructivism – a name rather disparaging from the viewpoint of the former.

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