Atomism at the End of the Twentieth Century

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> All things by immortal power,
> Near or far,
> Hiddenly,
> To each other linked are
> That thou canst not stir a flower
> Without troubling of a star.
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> Francis Thompson (1859–1907)

I. Nonlocal Entanglement: Wholeness in Space

Picture a rainbow: under ideal conditions, you will not only see the primary and the (fainter) secondary rainbow, but you will also realize there is a zone between the two which is considerably darker than the surrounding sky, and you will see the series of very faint and narrow bands of colors, usually pink and green alternately, at the inner side of the primary bow. For centuries these narrow bands, called "supernumerary arcs," have been a riddle to those who set out to explain the rainbow phenomenon scientifically.

In the seventeenth century, both Descartes and Newton were able to explain the primary and secondary rainbows and the darkening in between as phenomena of the spectral decomposition of light rays refracted and reflected by a large number of water droplets. However, there was no way to account for the supernumerary arcs with Descartes' and Newton's theories of light. In fact, a precise mathematical model of the rainbow has become possible only recently, with the aid of truly complicated computer programs. Qualitatively, the supernumerary arcs are due to an aspect of light that Newton's model of spectral decomposition could not provide. It is the wavelike nature of light as first proposed by Huygens (i.e., also in the seventeenth century) and demonstrated by Young in 1803 that gives an explanation in terms of the interference of light waves from the watery front of droplets: as Young himself pointed out, two rays scattered in the same direction by a raindrop are strictly analogous to the light passing through two pinholes (or a double slit) producing interference fringes.

Thus, whenever we see a rainbow phenomenon in its complete appearance, we witness the dual nature of light: its corpuscular (particle) nature can be seen as accounting for the primary and secondary rainbow (with the particles following the trajectories of the "light rays" in Descartes' and Newton's geometrical approach), while the wavelike nature of light is responsible for the supernumerary arcs.

Waves and Particles

The wave/particle duality is at the heart of one of the major physical theories developed in the twentieth century: quantum theory. This theory is the formal recognition of the fact that one can perform two qualitatively different kinds of experiments with light (or even with material "particles" such as neutrons or electrons, which are subject to the same kind of duality). For many years, one kind of experiment could be mathematically described only by assuming that light comes in discrete entities, the photons (in other words, the electrons are imagined as particles), and the other could be described only by modeling light (or electrons, etc.) as waves. The best known example of the latter is still Young's double-slit experiment that produces interference fringes. Einstein, on the other hand, showed the particlelike nature of light and electrons in 1905 when he correctly calculated the so-called photoelectric effect: whenever photons "hit" electrons, both must be considered as particles to obtain the correct energy transfers measured after their collision. Both Young's double-slit experiment and the photoelectric effect had been known before the advent of quantum theory in the 1920s. It was only with quantum mechanics, however, that by accepting the dual nature of quantum systems (i.e., photons, electrons, atoms, etc.) one obtained a mathematical framework that could account for all the phenomena observed.

Today, quantum theory (or its more modern versions, such as quantum electrodynamics, or the standard quantum field theories) is the most precise and most widely applied physical theory that has ever existed. Historically, its first big success was the explanation of several properties of atoms. In particular, Bohr's model of the atom in the beginning of the development of the theory (although still under wrong assumptions) provided the right numerical results for the lines in the spectrum of light absorbed or emitted by hydrogen atoms. In 1959, K.W. Ford and J.A. Wheeler showed, in a quantum mechanical treatment of atomic collisions, that a strong concentration of scattered atoms is expected near a special angle of reflection – much like "light rays" are scattered by water droplets to produce the rainbow phenomenon. In other words, there is also a "rainbow angle" in atomic physics that is correctly predicted by quantum theory.

Although the basic equations (as developed by Schrödinger, Dirac, Klein and Gordon, and more recently by Salam, Weinberg, and others) are partial differential equations describing the behavior of "wave functions" or "quantum fields," most of the further developments of quantum theories, up to present times, have been concerned primarily with the particle nature of quantum systems. That is to say that most emphasis has been put on the study of the fundamental "elementary particles" (or fundamental fields, along with attempts to unify the four fundamental forces in one theory: electromagnetism, strong and weak nuclear forces, gravity).* Thus, the ever-higher resolutions in space and time resulting from experiments at ever higher energies in particle accelerators (like CERN near Geneva or FERMILAB near Chicago) allowed a probing of the modern versions of quantum theory through investigations of smaller and smaller units of matter, such as today's "most fundamental" particle families, quarks and leptons.

Thus, despite the fact that there exist large unresolved questions regarding quantum theory (like the wave/particle duality and other enigmas to be discussed below), the scientific establishment, throughout the seven decades of the theory's existence, has pursued a policy of least resistance. It has put most of its energy (literally as well as in terms of financial resources, research posts, and prestige) into the one direction that was to provide new results as

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* Mathematically, these attempts at unification are formalized with the aid of so-called "symmetry principles." This has lead a considerable number of philosophically inclined physicists to proclaim the "disappearance of things" and the final victory of idealism. Factually, however, we witness the recurrence of a discussion that had culminated at the beginning of the twentieth century in the polemical critique of Mach's "empiriocriticism" by Lenin. (See Grössing, 1993, for a more detailed discussion.) Moreover, according to a well-known theorem by Emmy Noether, each symmetry principle is equivalent to a so-called conservation law. Idealists may wonder what the conserved quantities (like energy momentum, etc.) mean for the "disappearance of things."

soon as new barriers of space-time resolution, that is, of money and energy, were overcome. By ignoring a basic feature of quantum theory, namely that because of their wavelike properties the probing of quantum systems also means the probing of the apparatuses employed, high-energy physics has partly become a somewhat self-referential practice (and a somewhat self-fulfilling prophecy, too): the one-sided study of the particle aspects of matter only. All this has happened (and still happens) under the premise of what I want to call *"Twentieth Century Atomism": the belief (put into practice with the atom bomb, nuclear reactors, and particle accelerators) that the world, in its deepest essence, is composed of the tiniest entities – these "atoms" today being some kind of "elementary particles" – such that any object can be considered, at least in principle, as a spatially limited collection of a finite number of such entities.*

Ever since Democritus of Abdera (460–370 B.C.E.) introduced the concept of atoms in Western thought, later to be elaborated by Epicuros (as transmitted by Diogenes Laertius) and Lucretius, it lay at the basis of materialistic and atheist world views. Therefore, it may be less surprising to know that as late as 1624 in France, the teaching of atomism was a crime punishable by death. Even when atoms had been accepted, after the time of John Dalton (1766–1844), and indeed were considered indispensable by chemists, resistance against them continued among many physicists. Ludwig Boltzmann, who derived the laws of thermodynamics from the hypothetical existence of "atoms," was the foremost advocate of atomism in the nineteenth century, while another Austrian, Ernst Mach, was its most prominent opponent. Einstein's first articles were entirely within the Boltzmann tradition. As he explained in his autobiography, his work on fluctuations and Brownian motion was undertaken because of his desire to guarantee the existence of atoms of definite finite size. Boltzmann's statistical methods were also used by Max Planck for the quantum hypothesis of light, so "both roots of quantum theory, the Planck root and the Einstein root, go back to Boltzmann" (Boltzmann, 1981).

Nonlocality in Quantum Theory

The history of the debate on the interpretation of quantum mechanical formalism is very complex and involves almost as many different points of view as there are participants. For, despite quantum theory's large practical successes, the ontological status of what the theory actually describes is far from agreed upon. To some, quantum theory is merely a formalism describing objectively existing properties of matter, while to others it describes the observer's creation of a system or even indicates the existence of infinitely many parallel universes.

Much of the controversy has its roots in the Bohr-Einstein debate centering around the so-called "Einstein-Podolsky-Rosen (EPR) paradox." There is no room for a thorough discussion of this debate (which continues to this day), and the reader is referred to the widely accessible detailed literature or some of the good popular accounts thereof. However, the EPR "paradox" deserves our special attention, because it points to a property of quantum systems that is not well understood even today, that is, their so-called "nonlocality."

In a version put forward by David Bohm, the EPR problem considers a so-called "singlet state" consisting of two particles with opposite spin ("up" and "down") produced in such a way that the two particles, originally together, are moving apart. When you measure the spin of one particle (say, in the "up" direction) you immediately know the direction of spin of the other particle (i.e., "down") no matter how far apart the two particles are. So far this is not surprising. However, quantum theory has very subtle properties that are completely different from the classical view of the behavior of particles. Specifically, if one measures the spin of a particle along only one axis, say the x-axis, of a coordinate system that is used as a reference frame, one gets a definite answer (called an "eigenstate" of the particle), but one has lost the chance to know the spin's other components (i.e. along the y and x axes). This is because of Heisenberg's uncertainty principle, which allows knowledge of only one such component at a time. Which component one chooses is up to the experimentalist, but as soon as the measuring apparatus is prepared in a way to measure one eigenstate out of the three possible components, one is left uncertain about the other two.

Applied to the two-particle system in the EPR-case, this has dramatic consequences. For, whenever an apparatus on one side of the experimental setup measures a specific component of the spin (say + s), the other particle's spin automatically is in a corresponding opposite eigenstate (- s), because not only the total spins of the two particles, but also their x, y, and z components, are at any one time exactly opposed to each other. However, this means that whenever one particle is measured in an eigenstate (say + s), then – apparently without in any way interfering with the other particle – the other particle is in a well-known eigenstate (- s 0), *no matter how far apart the two particles have traveled since their separation*. In fact, their distance could in principle be thousands of miles or even lightyears, and still: as soon as one particle property is measured on one side, the eigenstate of the other will be affected on the other side. Since this effect apparently cannot be described by a local interaction of entities, one speaks in this case of the "nonlocality" of quantum theory. This situation is formalized in Bell's inequalities, which are today seen by most quantum physicists to prove the impossibility of a local theory explaining the EPR phenomenon. Moreover, in general, the nonlocality of quantum systems is not restricted to the case of the particles' spins, but can be implemented with other properties of particles, as in so-called "two-particle interferometry experiments."

With Erwin Schrödinger, we shall call the interaction-free particles in EPR-type experiments an "entangled" system, because they are entangled into correlated states. Furthermore, with Hans Primas, we shall call correlations into entangled states that have not been caused by direct interactions (i.e., in distinction to the singlet state described above) "EPR correlations." For there is another large class of phenomena that exhibits nonlocal features but is much less known than the famous singlet-state correlations. For example, in the molecular domain there exist EPR correlations between electrons and nuclei via their so-called "radiation fields." Usually, as in the Wigner-Weisskopf approximation describing the interaction of a molecule with the (theoretically infinite) radiation field of its environment, the latter is treated classically, thereby ignoring quantum mechanical terms for their assumed smallness.

Primas argues, however, that in a large number of cases such approximations are a tour de force that simply ignores what one does not want to see. As any scientific approach to natural phenomena operates with abstractions, it will provide agreeable results only as long as these abstractions are generally accepted and/or practical, or as long as there are no empirical results contradicting these abstractions. Primas (1987): ". . . natural science today is only possible if we break the holistic symmetry of nature. This symmetry breaking is produced by the *choice* of a certain view. A context-independent description of reality has proven to be impossible. Each context has its implicit preconceptions, which we chose as reference points for the description of nature. If one opts for other preconceptions, one chooses another context with a different perspective, so that nature is seen differently. Each context creates a picture of reality that is characteristic for that context." This, however, implies that even "atoms and molecules are manifestations of matter under a specific class of observational conditions." In the case discussed above, these conditions imply ignoring EPR correlations.

Is the Moon An Object?

If one does *not* ignore EPR correlations, one arrives at a picture radically different from the one to which we are accustomed: "According to quantum mechanics the electrons of the moon are entangled with their radiation field. If we are not willing to abstract from the quantum mechanical structure of this radiation field on the grounds that it is irrelevant for the problem under discussion, then the moon becomes entangled with the sun, etc., and cannot be said to possess an individuality. So without abstracting from the quantum structure of the radiation field, the moon cannot be an object" (Primas, 1987).

It would therefore seem that questions like "Is the moon an object?" should be more interesting to quantum physicists than questions like "Is the moon there when nobody looks?" Unfortunately, a large number of well-known physicists seem to be more concerned with the latter question, since they have transferred to the area of epistemological debate the finding that quantum systems are in an indefinite "superposition" of states (i.e., in some kind of "possibility space") as long as the systems are not observed. Thereby they have introduced an uncertainty in the distinction between descriptive symbols or date reduction systems on the one hand, and the described system or date on the other, so as finally to attribute the same ontological status to both matter and its description (e.g., a description by the wave function).

Only from such an epistemologically idealistic viewpoint is it possible to attribute a special role to the mind (consciousness, brain, etc.) of the observer of a quantum mechanical state. It is true that in a basic sense there can be no observation without observers, but one can nevertheless observe relational properties between (quantum) systems and the observing instruments, much in the same way as Roland Fischer describes the "fleeting process" of the "trans-substantiation" between quinine and the tongue: quinine is not "bitter" per se, but the relational process between quinine and the observer's tongue can be described as "tasting bitterness." Equivalently, any measured property of a quantum system must be considered as the result of the interaction between the system and the observing apparatus. Still, there is no necessity to doubt the "existence" of a quantum system's properties independent of observers, just as there is nothing gained by claiming that the quinine does not exist when it is not tasted or that the moon is not there when nobody looks.

Some physicists argue that one cannot ascribe the same ontological status to the moon and to a quantum system (like an electron, for example), because there is a difference between the classical world of macroscopic objects and the quantum world, with its peculiar characteristic of creating phenomena by measuring them. Such a division into classical and quantum worlds is not consistent, however.

Consider the example of the rainbow. It surely is a macroscopic phenomenon, but is it an "object like the moon" or a phenomenon of the interaction between light and matter like an observed quantum system? In fact, what is essential for a rainbow to be observed is that the observer's position is such that a set of directions exists along which light coming from the sun is strongly scattered into the eyes of the observer (or onto a photographic plate). Moreover, the appearance of the primary and secondary rainbows is not affected by the size of the droplets, but the thickness of the supernumerary arcs is. Thus, one can say that the size of the droplets partially determines how the rainbow looks, but the rainbow's visibility depends on the observer's position, just as the arrangement of a measuring apparatus (like a double slit) partially determines how the resulting interference fringes look, and the "visibility" of light coming through a double slit depends on the position of photon detectors or a screen behind a double slit.

In other words, the rainbow is a quantum mechanical phenomenon with the rain drops acting as millions of concave reflectors reducing the "possibility space" of the incoming light to specific spectral decompositions and interference phenomena. (If we were able to vary the rain drops at will, we could prepare different experimental situations so as to "create" different quantum states.) Similarly, however, the moon can be considered a quantum mechanical phenomenon: it is merely a roughly convex reflector, and it is only because of its distance and size that the observer's position is practically irrelevant and that interference phenomena, according to the wave-like aspects of matter, are too small for us to see.

This leaves us with the question posed above: is the moon an object? It must be stressed that this is *not* (at least not only) an epistemological issue, but is forced upon us if we take quantum theory seriously. In fact, we have already given an answer: *if one does not ignore EPR correlations, the moon is not an object.* Neither is any other constant of our perception, because, strictly speaking, there are no separable objects: an atom on the tip of your finger is literally linked with the faintest star, right now. Does this not only repeat the old saying that everything is connected with everything else? Well, yes, it is a restatement of the wholeness of nature, but it is also a challenge as to what we can do with this insight. For, as opposed to a purely philosophical statement, quantum theory gives us a picture of the world that can be put into practice. Questions now arise like "Why are there phenomena that can be treated as objects up to very good approximations?"; "When do these approximations break down?"; "When do EPR correlations qualitatively change what we would call objects were it not for their nonlocal entanglement with other regions of spacetime?"

We have seen that whether we treat observed phenomena as objects or not depends on what aspects or what practical purposes we are interested in. The practice of science, just as the practice of living in general, consists in the compression of complexity: we must make abstractions from the wholeness of nature to become operational. After all, there is no way to "understand" wholeness, and what we can behold of anything we perceive is of the same nature as what we can behold of the rainbow: a picture.

II. Fractal Evolution: Wholeness in Time

Imagine yourself somewhere in space and moving toward the earth. At some distance you would see only a point (with zero dimension). Only if you got closer would you perceive its roughly spherical shape (dimension three, as it is called). If you wanted to have a still closer look at this "sphere" and intended to start at its surface, you would, in turn, have problems with the qualification of dimension three. For: Where are the earth's limits? Do you take its clouds, with their turbulent character, into account; or should you disregard clouds as well as mountains for the sake of the idealization of a shape of dimension three? We see that even a simple description of the "object earth" depends on which of its aspects interest us.

B. Mandelbrot has coined the term "fractal" to describe a measure of irregularity and fragmentation. He has made use of an extended concept of "dimension" that should also hold for objects whose dimension is not a whole number. (For example, the degree of fragmentation of the coast of England is expressed in terms of a fractal dimension of roughly 1.5 instead of the dimension 1 for an unfragmented line.) It thus becomes clear that the dimension of an object also depends on qualities of the observing subject (its observing position, the degree of resolution, etc.) and that – again – objectifiable quantities now do not concern "objects for themselves" but only *relations between objects and observers*.

There is a particularly interesting class of fractals characterized by the "self-similarity" of its structures at different resolutions. This is the case with idealized mathematical objects like the so-called "Koch curve" or the "Mandelbrot set," but such self-similarities can also be found in a large number of natural phenomena such as coastlines, cloud formations, or the branchings of arteries, or neurons. In these examples one can find sectors with the same patterns of branchings and fragmentations at different magnifications. (In mathematical objects, such patterns are repeated even with the infinitely small.)

Fractals are used today in diverse fields of studies. They are particularly useful in the analysis of dynamic systems characterized by the generation of new structures ("self-organizing systems") and the corresponding non-linear behavior (as opposed to linear systems, where no new structures can appear) of such systems. Such systems are often studied in the framework of the so-called "phase-space," an abstract space that contains as its coordinate axes all parameters relevant to the description of the system (including, eventually, the three axes of ordinary space). Dynamic systems often are characterized by some coherent figure in that phase-space, and fractal dimensions are used to describe those figures quantitatively.

However, fractals are useful not only for the analysis of structures (i.e., of geometrical configurations, even if they represent compact information on the dynamics of nonlinear systems). They can also be seen from the perspective of time: the *construction* of a fractal pattern corresponds to an ever finer complexification of an initial figure. Considering the most abundant example of complexification, namely, the evolution of life, as the emergence of ever more complex forms of organization that in self-similar ways preserve themselves as autonomous units, then as an abstract description *evolution itself can be characterized as a fractal process of self-reference.*

As will be shown in the next section, one can even integrate inanimate matter into this scheme, because it can also be characterized by a tendency toward the "survival of the stable," as R. Dawkins describes the common characteristic of all life forms, and, according to J. Lovelock's "Gaia hypothesis," is also applicable to the whole of the biosphere. In this picture, therefore, quantum systems, perceiving organisms, and the earth itself represent organizationally autonomous, self-referential units as emergent products of the fractal evolution of the universe.

The Logic of Evolution

This evolution is characterized by the alternation of differentiating and integrating processes, which can also be formalized as a statement of an evolutionary logic. The "logic of evolution" describes the development from a symmetric state (i) toward a differentiated, asymmetrical state (ii), and finally toward a state of higher-order symmetry (iii) that "anti-symmetrically" integrates the former states of symmetry and asymmetry. There are numerous manifestations of such a logic of evolution. In each case, neither the second nor the third steps can be thought of without the preceding step(s). Such is the case, for example, with the evolutionary states of (i) asexual reproduction (i.e., symmetry between individuals), (ii) the appearance of male and female individuals (asymmetry), and (iii) sexual reproduction (integrating symmetry); or the "logic of world views" according to Günter Dux: (i) idealism (i.e., the identity between "inner" and "outer" world), (ii) realism (the external is not equal to the internal), and (iii) constructive realism (circular interaction between internal and external worlds).

Thus, the fractal unfolding of the world and its corresponding logic of evolution manifests itself in the development of "external" objects as well as "internal" states of consciousness (or forms of thought). As I have detailed elsewhere, one can therefore speak of "echoes" in the evolution of organizational units that recur again and again in various forms and often interact with each other, and which at some times contribute to the differentiation, and at other times to the integration, of processes in nature (i.e., in the "external world" as well as in our thinking).

Just as memory is the basis of the cognitive process in that the classifications of our experiences in the course of the sensory-motor interactions between subject and environment are interpretations of interpretations of interpretations (etc.) of ever earlier experiences, so any object's existence must be seen as based on ever earlier forms of existence. The picture of the fractal evolution of nature is thus a model of diachrony, or what rhetoricians call "metalepsis": the echoing of simple forms that grow more and more diversified over time.

Thus, the picture of an "object by itself" may be incomplete not only with regard to neglected EPR correlations but also with regard to its dynamics or its evolution. The wholeness in space must be complemented by wholeness in time to obtain a more adequate picture of nature within and without ourselves.

III. The Perception of Matter

If it is generally more adequate to describe organizational units in nature by the (diachronic) processes constituting them rather than by their mere (synchronic) structural characteristics, then this must also hold for the smallest known units, that is, for quantum systems. It has already been mentioned that the basic characteristic of all "units" is their tendency toward the stable (such as in living systems). A tendency, however, implies a process rather than a static quality. Moreover, recalling with H. Sachsse that oscillations are the basic prerequisites for the perception of an environment by living systems, one can again transfer this insight from biology into physics. With regard to entangled quantum systems, H. Primas notes that there exists "a deep formal similarity with the behavior in biological systems." Several years ago, I began to try to account for this formal similarity by posing the question: "How does a quantum system perceive its environment?"

I subsequently developed a model that I call "quantum cybernetics" to account for quantum systems as both waves and particles simultaneously, and for the circular, "perceptual" processes between the localizable "particle" and its generally nonlocal wavelike environment. The starting point is the observation by Maturana and Varela on the properties of autonomous biological systems: "If one says that there exists a machine M in which there is a feedback loop in its defining organization so that the output affects the input, then one in fact is speaking of a larger machine, machine M', which in the organization that defines it includes the environment and the feedback loop." Therefore I have proposed a cybernetic description of quantum systems closely analogous to biological systems: "A quantum system is a feedback system with a given reference signal that compensates for disturbances only relative to the reference point (i.e., a basic frequency), and in no way reflects the texture of the disturbance. Its behavior, then, is the process by which such a unit controls its 'perceptual data' through adjusting the reference signal."

How is nonlocality treated in quantum cybernetics? First, one has to note that, ever since the nonlocal features of quantum theory have been taken seriously, a discrepancy between quantum theory and the theory of relativity has haunted theoretical physicists. As it is generally believed that there cannot exist signals faster than the speed of light in a vacuum, the effect of nonlocal correlations (which seem to happen instantaneously, i.e., with practically infinite velocity) poses an apparently unresolvable contradiction. However, I have argued in several papers that this apparent contradiction can be resolved. For, if one carefully studies the principle of relativity, one finds that as a consequence thereof there must exist a universal quantity in the form of a *squared* velocity, c^2. As is well known, Albert Einstein has identified c with the speed of light in a vacuum and derived the special theory of relativity from its postulated constancy. This is perfectly legitimate and confirmed in numerous experiments. It is also clear from the theory that there can be no massive "particles" traveling with velocity c or faster. However, this still leaves c^2 rather than c as the universal constant which in principle can be decomposed not only into $c^2 = c \times c$ but also into two different velocities, $c^2 = u \times v$, where v is the particle's velocity much smaller than c and u is a velocity of "phase waves" much larger than c.

I have argued that these phase waves can account for a causal description of changes in nonlocal correlations on the basis of models of quantum systems by de Broglie, Bohm, and others. Basically, these phase waves are manifestations of the wavelike structure of what one calls the "vacuum" or "Dirac aether." I have more recently tried to describe these waves as "order out of chaos" phenomena so as to work out their basic dynamical qualities in a nonlinear theory. Of course, the underlying "hidden chaos" of a sub-quantum medium is of a purely hypothetical character (just as the theory of atoms was a century ago), but I have proposed experiments within the framework of quantum cybernetics to test whether or not such an "aether" exists.

At present, quantum cybernetics is just one in a series of attempts to provide a causal description of quantum processes via "hidden variables." Their common underlying assumption, however, is the existence of some sub-quantum medium. One can only speculate what this medium consists of, but there may well be further "smallest units" constituting it. What we today call "elementary particles" may therefore someday appear as nonlinear modifications of an apparently continuous medium that only upon further resolution would decompose into the "atoms" of the aether.

Thus, there may arise a new kind of atomism in the twenty-first century, with the atoms then being the "discrete" elements of the "continuous" sub-quantum medium. Again, one would be entitled to say with Democritus of Abdera that ". . . in truth there only exist atoms and the void." However, we might also realize that thereby we would only spin the wheel of controversies between adherents of the discrete versus adherents of the continuous by one more turn, thus fulfilling another cycle in the fractal process of cognition that spirals along the axis of time.

IV. The Evolution of Autonomy

As there are no objects in the sense of entities strictly limited by a certain region of space-time, there can be no atoms in the sense of the twentieth century atomism. Nevertheless, in our daily routines we get along quite well by treating things as objects – not to speak of ourselves as more or less well contained "self-conscious" beings. How can it be that in practice we hardly have any problem with the limitless features of our most elaborated physical theories?

Considering the entanglement of quantum systems, it is conceivable that in a model beyond quantum theory there exists a "noise term" to be added to nonlocal correlations such that with increasing distance between two elements of the entangled system (such as the two spinning particles in section I) noise increases, so that finally the correlations break down. Today, the range of nonlocal correlations is proven by experiment up to distances of 6 meters, so one can think of experiments over interplanetary distances, for example, to inquire whether entanglement persists or is faded out due to some "sub-quantum noise."

However, other possible mechanisms are known in present-day theories to produce fairly isolated objects. Both in high-energy – as well as in solid-state – physics, one speaks of so-called "dressed particles" when the "naked particles" of the ordinary theory strongly interact with their environment. Such is the case with collisions of particles at high energies, or with particles strongly bound to the potentials of a solid-state body. Thereby, parts of the environmental effects are added to the newly created object so that it becomes a "dressed particle." In general, it seems that, despite entanglement and EPR correlations, evolution has found ways to break down holistic symmetry by "self-organizing" objects into organizationally autonomous units. Consequently, one arrives at a characterization of evolution that is somehow opposite to the usual belief that more and more complex forms of organization arise. However, considering that the word "complex" is derived from the Latin "complector," that is, to put together, we see that a single electron is more "put together"(i.e. more complex) than a dressed particle in a solid-state body: an electron is EPR-correlated to the environment of its radiation field with infinitely many degrees of freedom, whereas a dressed particle's degrees of freedom are much reduced by the particle's "confinement" in the solid state.

Therefore, the more "complicated" (from the Latin "com-plicare," i.e., folding together) an object is (as opposed to "simple" or unrestricted with regard to EPR correlations), the fewer degrees of freedom of interaction with the environment there are, that is, the less "complex" such an object is. Thus, it is more appropriate to describe evolutionary processes in terms of the emergence and development of autonomous units with ever fewer EPR correlations: *evolution is a process of de-complexification into states of ever higher forms of autonomy.*

So, from a quantum mechanical point of view, the human brain (or, more "holistically," a person) is the most autonomous unit known to exist in that it is the least complex entity in the universe. It is still an open question whether quantum mechanics is relevant for the description of processes in the brain, but it may very well become relevant for more elaborate computing machines. For example, the recently developed "quantum cellular automata" which model complex systems consisting of discrete arrays of "cells" on the basis of quantum mechanical transition rules, may be studied with respect to nonlocal correlations. Other forms of "Nonlocal Computation,"* either in the brain or in computers, can

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*In an attempt to work out lower bounds for quantum effects in neuronal systems, I have recently proposed considering Nonlocal Computation as an emergent property of coupled neuronal modules. Moreover, a general paper on Nonlocal Computation with a detailed mathematical analysis of quantum cellular automata is in press.

be imagined, thereby envisaging qualitatively new forms of autonomy. One can thus think of autonomous "computing" units interconnected via entangled systems and EPR correlations so that they "self-organize" into forms of "nonlocal autonomy" we cannot even imagine today.

However, we still know very little about nonlocality. In particular, the entangled and EPR correlated systems studied today seem very simple compared to more complicated possibilities. Perhaps there exist even high-order correlations over nonlocal distances? One can imagine complicated systems whose EPR correlations with other similar systems couple in such a way that they constitute "meta-correlated" units, and so forth. Perhaps there exist EPR correlations on a genetic level between all the cells of an organism? And so on. There are numerous questions, numerous possibilities, but hardly any answers at present. It may very well be that one reason nonlocality has not been thoroughly understood for 70 years is because its implications are so dramatic and revolutionary that it will take much longer for them to dissipate into a broadly accepted picture of the world.

There exists a similarity between our situation today and the struggle of the heliocentric versus the geocentric world views in the time of Bruno, Galileo, Copernicus, Kepler, and others. As A. Koyré describes it, the heliocentric revolution had its own long history: "The celestial spheres which surrounded the world and held it together, therefore did not disappear at once in a mighty explosion; the world bubble was growing and swelling before it burst and broke up into the space surrounding it."

Thus, the breaking up of the celestial sphere, the disappearance of all limitations on the universe in the seventeenth century, can be seen as the "birth process" of a world-view that implied an identical nature in both earthly and heavenly objects. Similarly, the breaking up of any object's limitations via nonlocality echoes a birth process, a new world view now implying the factual, "synchronic" correlations between earthly and heavenly objects.

One may wonder if the notion of that birth process has a deeper, more abstract meaning. For, as the fractal nature of evolution is defined by the emergence of ever new organizational units, the "births" of the new world-views themselves are representations of such units.

What if one extrapolated this series of births of ever new forms of autonomy into a far future? Would there be a time when some units in the universe might become completely autonomous, that is, with no correlations whatsoever with their environment? If that were the case, these entities would themselves become "universes," and one may wonder if there would be anything one would miss in the world they had left behind.

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