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THE DIALECTICS OF FREEDOM*

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Ray Birdwhistell, one of the most distinguished of the creators of kinesics, saw human communication as composed of many channels of coherent behavior segmented asynchronously into units of durations varying from a few milliseconds up to four generations. Behavior patterns cannot change within an individual segment. But when the breaks between two or more types of these laminated segments overlap, choice and change become possible. He called this *the dialectics of freedom.*

I became acquainted with Birdwhistell's views when I had the privilege of sitting in on daily discussions between him, the ethologist John Crook and the linguist Ken Pike over a period of several months. I concluded my brief report of these discussions[1] with the remarks:

"...Since it is clear that simultaneity and punctiform space must be abandoned, this might imply that something equivalent to the calculus, but operating on the laminated set structure rather than on space-time, must be invented. One purpose of this paper is to point up this necessity; unfortunately my own mathematical talents are too limited to see how to proceed further than pointing out the problem..."

Thanks to the work of many people both inside and outside of ANPA, I believe that the mathematics needed for this task is now available. I spell out my reasons for this belief in this paper.

Recent work on classical determinism and quantum coherence has produced a paradoxical twist. The older view of quantum mechanics contrasts the fundamental uncertainty it predicts with the rigidly deterministic world of Newton and Einstein. Modern views tend to reverse these characterizations.

The older view stemmed from the Einstein[2]- Bohr[3] interchanges on the foundations of quantum mechanics. The debate led Einstein to remark that "God does not play at dice". Bohr felt that the truth was that we could never reconcile classical, deterministic physics with quantum mechanics; they were complimentary. He also said that "Truth and clarity are complimentary". Peierls has adjoined the remark that "Bohr always erred on the side of truth."

In the eyes of most practicing theoretical physicists Bohr had won the debate by 1935. Most physicists shifted their research interests to problems that they found to be both more exciting and more pragmatically rewarding.

The legacy of this debate was, for many years, the idea that indeterminism and in that sense irreducibly chaotic behavior lay at the heart of quantum mechanics. Eventually quantum mechanics was believed to be the fundamental theory and classical physics only an approximation. But this left two puzzles behind: if quantum mechanics is fundamental, why (as Bohr believed) is it necessary to assume the validity of classical physics in order to formulate the laws of quantum mechanics? and conversely, why is it so difficult to derive the classical equations from a well defined approximation within quantum mechanics? Or, why does classical determinism works so well in the every day experience?

The contemporary paradox is that we now are beginning to realize that solutions of classical equations are almost invariably chaotic rather than deterministic, while macroscopic quantum coherence has become, in a sense, even more rigid than classical determinism.

John Bell reopened the Bohr-Einstein debate. He reformulated — and from a theoretical point of view resolved — the issue in the a way that Einstein would have liked least: local determinism and classical statistics cannot be made compatible with quantum mechanics. Bell's Theorem had the additional virtue of suggesting to Clauser that the question could be tested *experimentally.* Clauser had minimal support for his experiment, even for a graduate student. Yet, for most of us, his experiment[4] proved that Einstein was *wrong.* No generally accepted subsequent experiment, including Aspect's, has done more than to confirm Clauser's result to higher accuracy in both the experimental and the logical sense. Since the quantum mechanical prediction for the observed correlations is *unique*, while the allowed range for classical theories is broad, these results make part of my case for the claim that quantum mechanics is more rigid than classical determinism.

The recent work on classical determinism I have in mind was made possible by the creation of very fast computers. Although investigations of this problem have a long history going back to work by Poincaré in the 19th century, the full force of the analysis of classical "deterministic" systems, which now can be recognized by the use of the buzz-word "chaos", has as yet struck only a few people as profoundly important. What is now known is that the future motion of most systems whose behavior is supposed to be "determined" by classical equations cannot in fact be predicted without supplying as much information about the initial state of the system as the "prediction" is supposed to yield. This renders "prediction" and hence "determinism" in the usual sense almost meaningless for most classical systems.

This fact impacts our beliefs about the foundations of quantum mechanics in a very direct way, as McCauley has recently pointed out[5]:

"...Born and Heisenberg argued strongly that physics should not be based on nonobservable concepts — because of this Max Born argued for the elimination of the continuum concept from physics. By restricting to computable numbers in classical physics, we take a small step in that direction. It means that formal Hilbert space theory cannot be the final foundation for quantum mechanics, because Hilbert space is built on the generalization to function spaces of the idea of the continuum, the completeness of the real number system (a space is complete when all the limits of all convergent sequences in the space also belong to the space). But this introduces noncomputability into the foundations of quantum mechanics, because almost all functions that can be defined are noncomputable (see Turing, 1937)."

In contrast to classical systems, the evolution in time of quantum systems has usually been discussed in such a way that the uncertainties in the starting point — which cause the rapid loss of information in chaotic classical systems — can be ignored. The deterministic evolution of the quantum state is assumed without question. The unpredictability is supposed to arise when the system is "observed" by a macroscopic classical system which freezes the result into some fixed, historical and repeatedly accessible material memory. Quantum mechanics then predicts the probability of finding in this memory one particular example of the outcomes which the theory allows as possible. This process of "observation" is called "wave function" collapse. Von Neumann followed this collapse back into the brain of the observer, and by implication to his "mind". We still suffer from the irrational speculations that this woolly thinking opened up to the dances of more and more woolly "masters".

This eagerness to grasp for "scientific support" for irresponsible and irrational wishful thinking reminds me of my father's chuckles when he told me about a 19th century British physicist, whose name I remember phonetically as "Crooks". This man had contributed significantly to late 19th century investigations of the electromagnetic spectrum, including as I recall X-rays. When he was knighted, he was given the Latin motto *Ubi Crooks, ibi lux* [Where Crooks is there is light]. But Crooks was also well known for his attempts to put investigations into paranormal phenomena on a "scientific" basis. I remember my father's delight in telling me that irreverent Englishmen rephrased his motto as *Ubi Crooks, ibi spooks.*

I hope that recent work of mine[6] may help to advance our understanding of these deep questions. I love light-hearted polemics, as I hope my remarks above make clear, but I have an even higher regard for rational consensus. My work stems from an unlikely root which goes back to the time when the pattern for over three decades of research into elementary particle physics and physical cosmology was set by the successful creation of "renormalized second quantized relativistic field theory". The predictive power of this theory has continually expanded during this whole period. Yet I think it fair to describe the theory as one in which you add infinities with one hand and take them away with the other in order to produce a finite result in agreement with experiment to high accuracy. Mathematicians are still arguing as to which hat the real rabbit was hidden under, and how it got there in the first place.

In 1948 Feynman showed Dyson a "proof of Maxwell's Equations" which Feynman refused to publish during his lifetime.[7] The proof starts from non-relativistic quantum mechanics and Newton's second law, yet ends up with the relativistic Maxwell equations in free space. As Dyson remarks after reconstructing the proof[8]:

"The Maxwell equations are relativistically invariant, while the Newtonian assumptions ..... which Feynman used for his proof are nonrelativistic. The proof begins with assumptions invariant under Galilean transformations and ends with equations invariant under Lorentz transformations. How could this have happened? After all, it was the incompatibility between Galilean mechanics and Maxwell electrodynamics that led Einstein to special relativity in 1905. Yet here we find Galilean mechanics and Maxwell equations coexisting peacefully. Perhaps it was lucky that Einstein had not seen Feynman's proof when he started to think about relativity."

Resolving the mystery starts by realizing that if we write Newton's second law for a *single* particle as force per unit mass (acceleration), describe field as the acceleration of a single *test-particle* whose ratio of charge to mass is fixed, and characterize single-particle quantum mechanics in terms of action per unit mass (i.e Planck's constant divided by the unique mass in question), then Feynman's proof only refers to length and time measurements. As is well known, if all we measure are lengths and times, it does not matter whether we use meters, feet, miles, light-years ..... for lengths or seconds, months, oscillations of a quartz crystal, years,.... for times, so long as we are consistent. This is called *scale invariance.*

In spite of the arbitrariness due to scale invariance, we can still single out a unique velocity by identifying it with the maximum velocity at which *information* can be transmitted independent of the units used. Similarly we can measure the area per unit time swept out by a line from a center to the particle when it is moving past that center with constant velocity. The constancy of this ratio is a special example of Kepler's second law. This allows us to define a second independent quantity which can always be determined no matter how we measure length and time. Remarkably, once we also fix the finite accuracy to which we can measure these two units (assuming some currently available technology), we get the formal properties called "quantum mechanics" above, but without the usual absolute limits on size associated with Planck's constant (Bohr radius, nuclear radius, Planck gravitational length,...). Further, the formal steps given by Dyson in his reconstruction of Feynman's proof loose their paradoxical character, as do the steps taken by Tanimura[9] in his extension of the Feynman proof to establish Einstein's gravitational geodesic equations. In short:

Fixed, finite measurement accuracy implies both Maxwell's electromagnetism and Einstein's gravitation.

We can now return to our paradox, and take another step toward resolving it. I assert that, from a modern point of view, any physical phenomena which go beyond what can be predicted from the action of electromagnetism and/or gravitation on a *single* particle *necessarily* bring in Planck's constant. Quantum phenomena set an *absolute* scale to the universe, which tells us under what circumstances the classical, *deterministic* equations are valid. In particular, as noted in our definition of chaos, this phenomenon arises when we try to get solutions out of the classical equations to such high accuracy that all the information is already contained in the initial conditions. If this fine grained specification violates the quantum restrictions, the classical equations break down, and *we must use quantum mechanics.*

Now we have come "full circle" to a higher point on our spiral of growing understanding. Classical determinism is self-contradictory once quantum phenomena are recognized. But quantum phenomena are *coherent*— a seamless whole for systems to which the theory applies. Thus they are more stable — and in that sense "more deterministic" — than the equations of classical physics allow. But if we go beyond the "coherence length" for these quantum systems, we get an assortment of laminated structures to which an approximate version of classical physics can be applied.

It is at the join between the two modes of description that our ability to manipulate the systems to what we hope is our advantage arises, as is made clear in recent papers on "controlling chaos". This is analagous to the behavior analysis of Birdwhistell with which we started. I dedicate this paper to his memory.

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