II. PHYSICS

The Third Storm of the Twentieth Century: The Einstein Paradox

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ABSTRACT

A paradox, according to dictionaries, is a surprising but perhaps true statement. Copernicus's heliocentrism was once a paradox. The problem with a true paradox is not in reducing it but in expressing it--as Einstein did with his relativity theory expressing the physical content of the Lorentz-Poincaré formulas of electrodynamics. Today again we have good formulas, those of quantum mechanics, but have not yet understood all their meaning. It is the paradox uncovered by Einstein at the 1927 Solvay Conference (and better known as the Einstein-Podolsky-Rosen [E.P.R.] paradox) which forces us to a dramatic revision of traditional ways of thinking about time.

The paradox emerges with special clarity from a conceptual experiment in which two spatially separated systems on the quantum scale are made to interact, but the only causal link between them is by way of an event in their common past. The paradox can be expressed in terms of the formal (de jure) symmetry between retarded and advanced interactions in physical theory, interactions which affect the future and the past respectively, independently of the de facto preponderance in nature of retarded interactions. The possibility that advanced interactions may occur de facto in large-scale systems is briefly discussed.

* Lecture delivered at the Third Conference of the International Society for the Study of Time, Alpbach, July 1-10 (1976).

Suppose we perform an experiment in which an atom located at a point C emits two successive photons which go to two different places, L and T, where there is apparatus to measure their polarizations. Suppose further that the atom is known to have the the same angular momentum after emitting the two photons as it had before: we then know that if we measure, say, the *x*-component of the spin of one photon at L, we can predict that a corresponding measurement on the other photon at T will give the negative of the value found at L. Now it is proved in quantum mechanics that one cannot simultaneously measure, or even assign values to, the different components of the spin of a particle. But one can choose one component to measure at L and predict the value of the corresponding component at T. This led Einstein, Podolsky and Rosen[1] in a classic paper in 1935 to assert that if by making a choice at L we can predict the value of any of the three components at T, it follows that the photon bound for T *has* a property which determines these three components of spin even though experiment may allow us to reveal only one of them. This property is not the polarization itself, for we know that polarization follows the "paradoxical" laws of quantum mechanics, but something belonging to the classical world of physical properties which determines the result of any measurement we may choose to perform. Because we are not supposed to know about this property directly it is called a *local hidden variable:* local because it is carried by each particle separately. This variable is assumed to be distributed statistically but not at random, for in discovering the value of the polarization at L we learn enough to be able to predict that measured at T. Thus the random event happens at C when the two photons start out; after that everything is causally determined. In 1965 J. S. Bell[2] showed that this reasonable explanation is incompatible with the theory of quantum mechanics, and work in recent years has shown it to be incompatible with experiment also: the die is cast not at C, when the values of the local hidden variables controlling the polarization would have to have been determined, but later, when a measurement is made at T or L. In this sense, the correlation between the measurements at L and T is not only a "telediction", but also (paradoxically) a "teleaction". Bell's theorem provides a quantitative severance between classical statistics and the new wavelike statistics, the experimental evidence being in favor of the latter.

Like other fundamental laws of dynamics, the laws of the electromagnetic field allow two sorts of solution symmetric to each other with respect to past and future. Needless to say, the one in which a moving charged particle generates a wave which subsequently spreads out in space, called the retarded wave, is the one we are used to. The one symmetric to it, the advanced wave, has the exactly reversed behavior. Originating in the environment or in the depths of space, it converges on the point where the charge will be at the moment the wave arrives, as if the universe knew in advance what the charged particle was going to do. But if we place the particle and move it about as we choose, the universe cannot know *this--perhaps we were not yet* born when the wave started out. Thus the only possible physical interpretation for the advanced wave is that of a causality operating in the reversed direction of time: the moving charged particle determines, *here and now*, the events in the distant past which generated the converging wave.

The only logical, mathematical and physical channel for the correlation between the events at L and T consists in the two timelike vectors LC and CT, and implies a *de jure* equality between retarded and advanced waves in the individual stochastic event (called a quantum). The *de facto* preponderance of retarded over advanced waves, and of increasing over decreasing entropy, is a *macroscopic* property of nature as we know it.

However, the *de jure* symmetry displayed by the E.P.R. paradox (and indeed expressed in the very formalism of the theory) raises the possibility of an "anti-(second law) physics" symmetric to the ordinary physics which derives its time sense from the increasing entropy postulated by the second law of thermodynamics, very much as the *de jure* symmetry between positive and negative energies in Dirac's theory led to the explanation of antiparticles as symmetric to particles.

At the 5th Solvay Conference in 1927, Einstein[3] uncovered a paradox which is inherent in the very essence of the new quantum mechanics and which today, having been thoughtfully pondered quite a few times, truly appears as *The Paradox of the New Quantum Mechanics*. It is what the absence of an optical ether wind was to special relativity, or the riddles of heat capacity of radiation and material bodies were to the old quantum theory.

In physics a good, true, paradox always heralds the coming of a new "paradigm." In the dictionary sense, a paradox is "a surprising, but perhaps true statement". Copernicus' heliocentrism was one such. Through paradoxes science is urged, like Nicodemus, to be "born anew". The problem, then, is not in trying to reduce the paradox, but rather in formulating it adequately. This is what Einstein did by unveiling the true sense of the Lorentz-Poincaré formulas, and what Planck did by introducing the quantum discontinuity into electrodynamics. In this way the smoke of the paradox is changed into light--perhaps a dazzling one, but it gives a new view of things.

My contention here is that, very much as in the days of Lorentz and Poincaré, we possess the right formulas--those of the Heisenberg, Schrödinger and Dirac quantum mechanics--but have not understood yet their complete import. This, the paradox uncovered by Einstein in 1928, now forces us to do.

Lord Kelvin,[4] in 1900, said he saw two clouds in the sky of theoretical physics, pointing exactly to where the two storms of quantum mechanics and of special relativity were ready to burst. The Third Storm of the 20th Century, now over our heads, has been rumbling since the very days when the Tables of the Law of the new quantum mechanics were laid down. Some more lighting was needed, however, to clarify the sense of the Scriptures--that is, some more work on the Einstein Paradox.

I will explain the paradox by using a little fable. At midnight G.M.T. two travellers (Figure 1) leave Calcutta, C: one for London, L, and one for Tokyo, T, each carrying

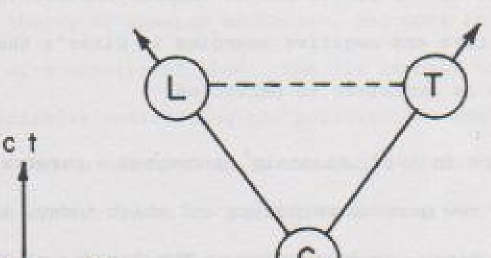

Figure 1

a closed box containing, or not, the ball which a third man has previously placed in one of them, behind a veil. At 6 G.M.T., having landed at his destination, each traveller opens his box and immediately learns what the *other* one finds. The point is that the instantaneous inference is a contraction of the explicit reasoning, which does not follow, in space-time, the spacelike vector LT, or TL, but rather the two timelike vectors LC and CT (or TC and CL), once towards the past, once towards the future. For drawing his inference each traveller must remember his flight from Calcutta and what was done there, and imagine the flight of the other one from Calcutta. Not only is the LCT (or TCL) zigzag followed by the reasoning (or the calculation), but also it is the one really traversed by the airplanes. By contrast, the direct, spacelike path, LT, is empty in all three respects. There is still no paradox in this, however, because in this classical information-theory problem it is at C that, so to speak, the die is cast, once and for all. In Bell's[2] words, we are dealing with a local hidden-variable theory, the hidden variable having the value 0 in one box and 1 in the other. We thus have between L and T pure telediction, and not teleaction.

It is at this very point that quantum mechanics upsets our ingrained habits of thought. Far more than a mere wave mechanics, it is a *new wavelike probability calculus*, some rules of which are similar to, but some drastically dissimilar from, those of the classical probability calculus.

The new quantum mechanics has it that in the quantum analogue of the ball and two boxes the die is cast not at C, but later, where and when the measurements are made, that is, at L and/or T. This is the Einstein[3] paradox (better known as the E.P.R. paradox) which in later years he[5] still considered an unacceptable one, as entailing, (said he) either "telepathy" between observers at L and T, or denying "independence as such to things spatially separated." Schrödinger,[6] in the meantime, having independently hit upon the same paradox, said he saw (unacceptable) "magic" in the (accepted) Copenhagen doctrine, which, wrote de Broglie,[7] would "upset our familiar notions concerning space and time". These words, by eminent physicists, should be seriously pondered today in the light of Bell's[2] crucial theoretical severance between quantum mechanics (Q.M.) and local hidden-variable theories (L.H.V.T.), and of the ever-increasing experimental evidence in favor of quantum mechanics.

Why quantum mechanics implies that, in the E.P.R. context, the die is cast not at C [where classical statistical mechanics (C.S.M.) had it], but rather at L and/or T, stems from the very existence of "non-simultaneously measurable magnitudes," and from the open choice that allows an observer to wait until the last moment before deciding what magnitude he will measure. In the present tests of the E.P.R. paradox, what is measured at L and T is, in fact, "position plus polarization" of correlated protons,[8] or photons issuing from a cascade transition[9] or an e^+e^- annihilation at C.[10] A photon either passes, or not, a linear polarizer, thus giving a yes or no answer to the question "is your linear polarization parallel or orthogonal to some direction ℓ?" By giving his polarization detector an orientation ℓ the experimenter at L can determine one, but not more than one component of the photon spin at L, and hence at T. Since the orientation ℓ may (in principle) be set while the photon is flying from C to L, it is obvious that quantum mechanics, as it stands, implies that we have between L and T not only telediction, as was the case with classical statistical mechanics, but truly *telediction plus teleaction*--whence the horrified, and extremely specific, words of Einstein,[5] Schrödinger[6] and de Broglie.[7]

It is true that up to now the crucial experiment, where the orientations of the polarizers are changed while the correlated photons are flying from C to L and T, has not been performed. Such an experiment has been designed,[11] however, and the building of the apparatus has begun. In the meantime one is allowed to lay bets. As quantum mechanics is by far the most precise sort of probability theory ever used in physics, my bet is in its favor: that nothing new will be observed. And I will draw some consequences that follow if I am right.

The existing experimental evidence is today considered to be in favor of Q.M. because of Bell's clever theorem, which he later[12] cast in the following didactic form: Denote symbolically by $\mathscr{L}$ and $\mathscr{T}$ the results of the measurements at L and T, ℓ and t the corresponding orientations of the polarizers, and λ the values of a set of hypothetical hidden variables specifying at the instant (in the laboratory frame) of the two measurements, the states of the measured system and the measuring devices. Under the assumption

$$\mathcal{L} = \mathcal{L}(\lambda, \ell) \qquad \mathcal{T} = \mathcal{T}(\lambda, t)$$

it is *not* possible to reproduce the quantum predictions, but under the assumption

$$\mathcal{L} = \mathcal{L}(\lambda, \ell, t) \qquad \mathcal{T} = \mathcal{T}(\lambda, \ell, t)$$

it *is*. And as this is a *non-locality statement*--the result in London depends on the value of something in Tokyo and vice versa--the hidden-variable remedy is no less paradoxical than the quantal illness it was aimed at curing. As we have said, the experimental evidence up to now is very strongly in favor of Q.M.

So, contrary to the common sense feeling *and* to what Einstein, Podolsky and Rosen[1] stated as an unquestionable assumption, *the measurements at* L *and* T *with a spacelike separation are not independent*. Moreover, as previously said, the only non-empty channel joining L and T consists of the two timelike vectors LC and CT or (TC and CL), so that this connection occurs along the zigzag line LCT, one line towards the past, one towards the future--thus upsetting, in de Broglie's[7] words, "our familiar notions concerning space and time". I[13] have proposed this interpretation quite a few times since 1953, and today Stapp,[14] Bell[15] and Davidon[16] have come to similar conceptions.

At this point it should be obvious that a tight connection exists between the Einstein paradox and the older paradox of lawlike time symmetry in microphysics versus factlike time dissymmetry in macrophysics. Let us recall what the older paradox was, and then examine what new traits are added when a wavelike probability calculus replaces the old one.

The paradox in classical statistical mechanics has received the well-known Loschmidt[17] and Zermelo[18] expressions. The point is, however, that the paradox was already present in the classical theory of probability *per se*, without reference to any specific dynamics. Consider for instance the shuffling of cards. The probabilities that a card will go from rank *r* to rank *s* or from rank *s* to rank *r* are assumed equal, and also the same as that a card has come to rank *s* from rank *r* (there is no reason to believe *a priori* that predictive and retrodictive probabilities are the same.) Then, given any arbitrary configuration of the deck as being "in order", *blind statistical prediction* (in Watanabe's[19] words) will very well describe the effect of shuffling, while blind statistical retrodiction would be contrary to ordinary facts. Nobody will rely on shuffling for putting the deck in order at will. This is why classical authors treated retrodictive problems completely differently from predictive ones; they called them problems in the probability of causes, and introduced Bayes's extrinsic probabilities for solving them. These extrinsic probabilities were chosen to describe as well as possible the interaction out of which the system under study had emerged, and the prescription to use them in retrodiction rather than in prediction implied that interactions produce after-effects and not before-effects. It implied causality. To my knowledge van der Waals[20] was the first to recognize that the statistical derivation of the *H*-theorem rests on a temporal application of Bayes's conditional probability statement. In other words, far from being *deduced*, statistical irreversibility is *postulated*. It is expressed in the form: *blind statistical retrodiction is forbidden* or, in other words, as the following boundary condition: any arbitrarily heterogeneous configuration may be chosen as an initial, but not as a final condition, for integrating the statistical evolution equation.

A quite similar statement exists in the classical theory of waves, for integrating the wave equation. Thus it is only natural to ask if perhaps there is not a physical link between the two statements. All sorts of examples support this view, for example: between times t_1 and t_2, a piston is moved in a cylinder containing a gas in equilibrium. The fact (if not the mathematical truth) is that Maxwell's velocity distribution is perturbed after time t_2 and not before time t_1. And the fact is also that this interaction is propagated as a retarded pressure wave emitted, and not as an advanced pressure wave absorbed, by the piston.

In the 1905's a bitter controversy[21] opposed Ritz, maintaining that retarded waves are postulated in the derivation of the Second Law, to Einstein, holding conversely that wave retardation should be understood as a statistical effect. Both opponents (somewhat overlooking the factlike rather than lawlike[22] character of their respective assumptions) thought to be contradictory reasonings which in fact were reciprocal to each other. This was because, though Einstein's photons were known by then, de Broglie's matter waves were not. Statistical scattering of particles and of waves were thus not seen to go hand in hand.

The tight connection between the two irreversibility statements is also implied in Planck's[23] thinking, and is made explicit in his expression for the entropy of a light beam, which is increased by scattering.

However, in this field also the Old Covenant has to yield to the New Covenant of quantum theory. Then the lawlike (microphysical) time symmetry versus the factlike (macrophysical) time dissymmetry turns out as even more paradoxical than before.

In quantum mechanics a wave function ψ is postulated to specify *all* the information that can be specified about the physical system it describes. Normally, this information is in the form of statistical statements: the probability that the electron will be inside a certain cubic centimeter of space at 10:30 is such-and-such. But suppose we now observe the cubic centimeter at that moment and find the electron. The structure of probabilistic statements contained in the wave function collapses: the electron actually is there, and statements about probabilities are no longer relevant. This sudden change of the state of our description is known as the collapse of the wave function. Is this event endowed, like the collision of classical statistical mechanics, with an intrinsic time symmetry? Yes, indeed. This intrinsic time symmetry has been written since the beginning in the Tables of the Law, but nobody yet has taken proper notice of it.

Is, then, factlike time asymmetry a purely macrophysical statement, implying ensembles, plus a specific boundary condition? Yes, indeed. And this also was written long ago in formulas, the meaning of which was not fully grasped.

Let us discuss the ψ collapse in the example that fits best the present context: position-plus-spin measurement of a relativistic particle[24] (of possibly zero rest mass[25]). The formula solving the Cauchy problem [24,26]

$$<x|a> = <x|x_0><x_0|a> \tag{3}$$

can be interpreted[24] as expanding the wave function $\psi_a(x) \equiv <x|a>$ at any point-instant x on the complete orthogonal set of Jordan-Pauli propagators $<x|x_0>$ such that

$$<x|x'>=<x|x_0><x_0|x'> \quad \text{iff } x\text{-}x' \text{ spacelike,} \tag{4}$$

the coefficients of the expansion being the values $<x_0|a>$ of $<x|a>$ on a space-like surface σ.

Thus, if the particle is found to cross a given element of σ centered at x_0, the corresponding eigenfunction is $<x|x_0>$. And as $<x|x_0>$, zero outside the light cone, is non-zero inside *both* future and past, this says that the particle will go inside the future, and has arrived inside the past light cone. This may sound trivial but it is not, because *something is implied which everybody has overlooked:* the ψ-collapse occurring at x_0 affects the future (of course), and symmetrically the past also.

This is the key I am proposing not for reducing, but for expressing the Einstein paradox--which its discoverer did not believe to be a paradox as we are using the word. There is no other choice, however, than accepting it--either for good or for evil, depending on one's taste.

I need not say that intrinsic time symmetry is explicit in many of the formulas of quantum field theory, and not only confined to the present discussion.

Whence, then, comes probability increase and wave retardation? From statistics on ensembles and a specific boundary condition.

Von Neumann's[27] entropy increase in quantal measurements is derived under the assumption that the collapsed waves of the ensemble are used for (blind statistical) prediction rather than for retrodiction. Thus it is a macrophysical statement, where irreversibility stems again from a time-dissymmetric boundary condition. What is novel is that the new quantum mechanics, being a wavelike probability calculus, produces entropy increase and wave retardation as two facets of one and the same irreversibility statement.[28] Fock[29] *and* Watanabe[19] have both pointed out that in quantum mechanics retarded and advanced waves should be used respectively for blind statistical prediction and retrodiction, which of course has this same implication.

Now I come back to the discussion of the Einstein paradox and the recent experimentation pertaining to it. The correlation between the two position-plus-spin measurements at L and T consists in that both produce the same wave collapse--in their common past. This is implied in the experiments already performed, and is the *truly* paradoxical fact which would be unambiguously established if quantum mechanics turns out as once more vindicated by the experiment[11] in which the polarizers will be turned while the photons are in flight between C and L and T.

That such a conclusion is of general rather than exotic significance is made obvious if we remark that two (or more) observers of *any* quantal measurement are E.P.R. correlated. This is exemplified in Figure 2, picturing the observation of impacts of α particles on a scintillation screen. If one of the observers sees a scintillation on the screen, then the other must see it also.

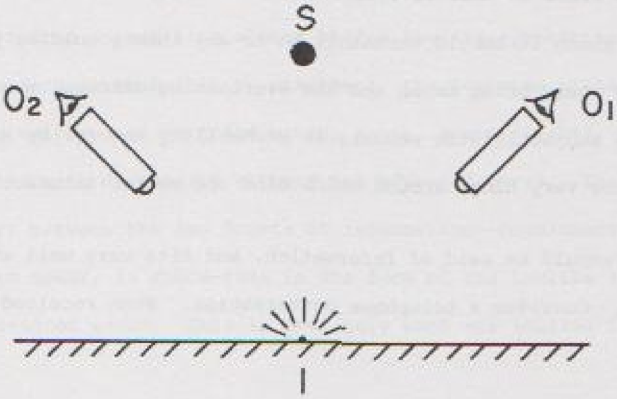

Figure 2

Finally, what overall philosophy is implicit in the findings under discussion?

Let me recall that there is, in relativistic quantum mechanics, another striking example of a lawlike symmetry somewhat hidden behind a large factlike dissymmetry--and a case where unravelling the lawlike symmetry has revealed a new world. In Dirac's theory (and even more so in Feynman's presentation of it) the positron is the exact lawlike twin of the electron. In fact, however, it is much rarer. But today we easily find it, because we know well where to look for it and how to produce it. We thus have learned that the world of anti-matter does make some incursions inside our familiar world of matter.

By analogy with anti-paricles let me define (macro) anti-physics as the paradoxical doctrine obeying a "reversed Second Law". As we have already seen, at the elementary level, quantum mechanics does have, symmetrically and essentially, one foot in physics and one foot in anti-physics--just as was the case with positive and negative energies. It is then only natural to inquire if, perhaps, (macro) anti-physics does not make some incursions inside our familiar world of physics. Then the problem is, where should we look for it, and what should we do?

Von Neumann[27] and London and Bauer[30] have it that the ψ collapse is due to "the act of consciousness of the observer when he takes cognizance of the experimental result". I believe this statement to be right on one point and quite wrong on the other.

What is wrong is that, as it stands, the statement is time asymmetric, which it should not be. What is right is that it views the stochastic event as *indissolubly objective and subjective*--which it should certainly be in any theory holding probability as essential. This would bring to an end the everlasting discussion between the objectivistic and the subjectivistic schools in probability theory, by stating that probability is the very hinge around which mind and matter interact.

The same, then, should be said of information, and fits very well what information theory tells us. Consider a telephone conversation. When received, the signal along the wire (with a negentropy assigned to it) is decoded and understood. This is the learning transition, where *information as knowledge* is extracted, according to the symbolic formula

$$N \to I_2 .$$

When emitted, the signal was coded from conceived information, and what we have is information as an organizing potentiality according to the willing transition

$$I_1 \to N .$$

With the advent of cybernetics the notion of information as knowledge has become quite trivial--the man in the street buys a newspaper for a few cents to find "information" in it, while information as organizing power has become a rather esoteric concept, used by those few philosophers interested in will or in finality. Why this accident has occurred is fairly obvious; it is because of the factlike physical irreversibility, according to which

$$I_1 \geqslant N \geqslant I_2 .$$

The learning transition is thus seen to be a slight generalization of the Second Law (part of the decaying negentropy being saved as knowledge), while, isolated from the surroundings, the willing transition would go straight against the Second Law. We know well, however, from the theory of antiparticles, that the creativp approach to physics does not start from merely taking as granted the overall factlike situation, but rather from unravelling almost hidden lawlike symmetries. Just as, according to von Neumann's irreversiblity statement, the learning transition is associated with increasing entropy and retarded waves, so is, symmetrically, the willing transition accociated with decreasing entropy and advanced waves. In other words, the lawlike symmetry between the two facets of information--cognizance and will--is projected, so to speak, in space-time in the form of the lawlike symmetry between retarded and advanced waves. This is precisely what was implied in our previous discussion of the ψ-collapse. At the elementary level, the spark, so to speak, of the act of consciousness is indissolubly cognizance *and* will, source of a retarded *and* sink of an advanced wave. Schopenhauer's title, *The World as Will and as Idea*, looks very appropriate when seen in this light.

It has been said humorously that Einstein, in discovering Relativity in 1905, had lost the subject of the verb *to undulate*. When Born rediscovered it in 1926, it was in a form far more "subtle" than that of the lost ether: a probability amplitude, obeying the superposition (or interference) law from which spring almost all quantal extravagances. My contention then, is that the new wavelike probability calculus has much to teach concerning the world we live in, and the way in which mind and matter interact.

Let us consider the Schrödinger[6] cat paradox. Schrödinger imagines a cat in a box with a gun pointed at it, and, attached to the trigger, a counter which can detect radiation from some atomic nucleus. Whether or not the radiation is emitted is a matter of chance: the wave function of the nucleus contains two parts describing the situations in which the radiation has and has not been emitted. And, correspondingly, the poor cat is described by a wave function which is part live-cat and part dead-cat. It continues in this ambiguous condition until someone opens the box and looks in. Only at this moment is the die cast: the wave function collapses and the cat is truly alive or truly dead. What is obviously wrong in Schrödinger's presentation of it is that the cat is as good a wave collapser as anybody else. He has some sort of consciousness, and certainly knows (in its own way) when he is alive, and also, as it seems, if he is being killed. If, then, Schrödinger's observer is looking at the radioactive decay (which triggers or not the lethal weapon) along a channel parallel to the cat's, then both cat and observer are E.P.R. correlated. They are cooperating or competing to produce the same ψ-collapse--in their common past.

One guesses that in this, the cat is more motivated than his tormentor, and that a normal cat will favor the issue which leaves him alive. Thus, he will try to call in, from the past, the appropriate advanced wave.

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